Robust and blind image watermarking in DCT domain using inter-block coefficient correlation

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a b s t r a c t

This study presents a robust and transparent watermarking method that exploits blockbased discrete cosine transform (DCT) coefficient modification. The difference in the DCT coefficients of two blocks is calculated and modified based on the watermark bit to adjust this difference to a predefined range. The first coefficient in the upper left corner of the array basis function is known as the direct current (DC) coefficient, whereas the remainder includes the alternating current (AC) coefficients. The extent of the DCT coefficient modifications depends on the DC coefficient and median of the AC coefficients ordered by a zig-zag sequence. The robustness of the proposed method against various attacks was evaluated experimentally, and experimental results demonstrate that the proposed method possesses great robustness against various single and combined attacks.

這項研究提出了一種強大的且透明的水印方法，該方法利用了基於塊的離散餘弦變換（DCT）係數修改。 根據水印位計算並修改兩個塊的 DCT 係數差，以將該差調整到預定範圍。 數組基函數左上角的第一個係數稱為直流（DC）係數，其餘的包括交流（AC）係數。 DCT 係數修改的程度取決於 Z 字形序列排序的 DC 係數和 AC 係數的中位數。 實驗評估了該方法對各種攻擊的強大的，實驗結果表明，該方法對各種單一攻擊和組合攻擊具有較強的強大的。

1. Introduction

Copyright violations have increased owing to the recent advancements in Internet technologies. Digital property can be easily distributed globally. Consequently, digital image watermarking is used to prevent the copyright violations. Watermarking involves embedding information to protect the ownership and integrity of the digital content. Watermarked content is nearly the same as the original content, and digital watermarks are difficult to detect and remove without damaging the original content. A content owner can embed the ownership information into digital content, such as images [10], video [4], and audio [8], using a digital watermark. Effective watermarks should be robust against alterations and imperceptibility [15].

由於互聯網技術的最新發展，侵犯版權的行為有所增加。 數字財產可以輕鬆地在全球範圍內分發。 因此，使用數字圖像水印來防止版權侵犯。 加水印涉及嵌入信息以保護數字內容的所有權和完整性。 帶水印的內容幾乎與原始內容相同，並且在不損壞原始內容的情況下很難檢測和刪除數字水印。 內容所有者可以使用數字水印將所有權信息嵌入到數字內容中，例如圖像[10]，視頻[4]和音頻[8]。 有效的水印應具有魯棒性，以防篡改和不易察覺[15]。

Watermarking techniques involve spatial and transform domains. In the spatial domain, a watermark is embedded in an image by directly modifying the pixels [12,18], whereas in the transform domain, watermark is embedded by modifying the coefficients of the transformed image [16,17]. Spatial domain techniques have lower computational complexity than the transformed domain techniques but tend to be less robust. On the contrary, the transformed domain techniques feature higher computational complexity with greater robustness.

水印技術涉及空間域和變換域。 在空間域中，通過直接修改像素[12,18]將水印嵌入圖像中，而在變換域中，通過修改變換圖像的係數[16,17]嵌入水印。 與變換域技術相比，空間域技術具有較低的計算複雜度，但穩定性較差。 相反，變換域技術具有較高的計算複雜度和較強的魯棒性。

Herein, we focus on a transform domain watermarking scheme. Several transform techniques, such as Fourier transform (FT), discrete wavelet transform (DWT) [6,19], singular value decomposition (SVD) [1,3,9], and discrete cosine transform (DCT), have been proposed. There are several types of FT, such as discrete FT, fast FT, fractional FT [11], and quaternion FT [20]. FT is robust against common image attacks but not against geometric attacks, such as JPEG compression and rotation.

在此，我們集中在變換域水印方案上。 已經提出了幾種變換技術，例如傅立葉變換（FT），離散小波變換（DWT）[6,19]，奇異值分解（SVD）[1,3,9]和離散餘弦變換（DCT）。 FT 有幾種類型，例如離散 FT，快速 FT，分數 FT [11]和四元數 FT [20]。 FT 能夠抵抗常見的圖像攻擊，但不能抵抗 JPEG 壓縮和旋轉等幾何攻擊。

H.-J. Ko, C.-T. Huang and G. Horng et al. / Information Sciences 517 (2020) 128–147

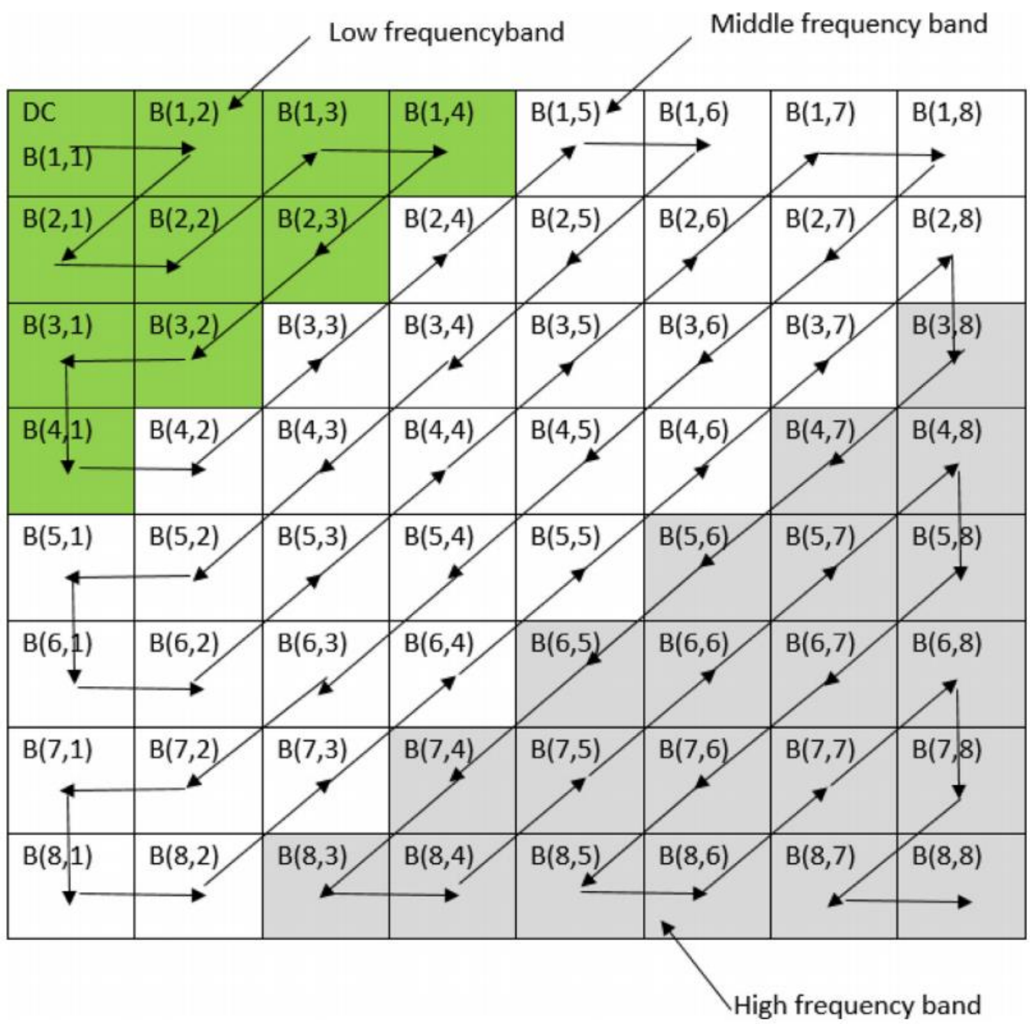


Fig. 1. Zig-zag ordering for DCT coefficients.

DWT is used for JPEG2000 and requires more transformation time than DCT. The SVD method is a matrix factorization that can be designed as a reversible watermarking technique. However, SVD is more complex than DCT and DWT; therefore, it is not suitable for software and hardware implementations in low-cost devices, thereby making DCT popular in the transform domain [7,13,14].
DWT 用於 JPEG2000，並且比 DCT 需要更多的轉換時間。 SVD 方法是一種矩陣分解，可以設計為可逆水印技術。 但是，SVD 比 DCT 和 DWT 更複雜。 因此，它不適用於低成本設備中的軟件和硬件實現，從而使 DCT 在變換域中很流行[7,13,14]。

DCT can be computed on the entire image or non-overlapping blocks of a specified size. After DCT is performed, a block can be separated into low, middle, and high frequency subband coefficients. Coefficients changed in the high frequency subband will not significantly degrade image quality. On the contrary, the low frequency subband comprises most of the image and any change in this subband will change the image quality significantly. To obtain a high quality and robust watermarked image, middle frequency subband coefficients are most suitable for embedding watermark bits.
可以在整個圖像或指定大小的非重疊塊上計算 DCT。 在執行 DCT 之後，可以將一個塊分為低頻，中頻和高頻子帶係數。 高頻子帶中變化的係數不會顯著降低圖像質量。 相反，低頻子帶包含大部分圖像，並且該子帶中的任何變化都將顯著改變圖像質量。 為了獲得高質量和魯棒的水印圖像，中頻子帶係數最適合嵌入水印位。

Recently, several watermarking methods have been developed. Golabi et al. [5] proposed a watermarking method based on the features of radical moment. This method is robust against rotation and scaling attacks. However, moment-based techniques are not robust against cropping attacks. Furthermore, the total watermark bits can be embedded into a 512 × 512 cover image only 127 bits. Patra et al. [14] proposed a DCT watermarking scheme based on Chinese remainder theorem (CRT). In the scheme, the host image is divided into 8 × 8 pixel blocks, a block is selected, and DCT is applied randomly. Then, a watermark bit and DCT coefficient are selected, and CRT is used to calculate the amount of modification based on several conditions. This scheme has low computational complexity and is robust against common image processing attacks. This scheme is robust against 10% cropping attacks; however, it has not been tested against 25% cropping attacks. Das et al. [2] proposed a watermarking scheme based on the inter-block coefficient correlation in DCT. They only changed one coefficient in each block based on the predefined threshold. This scheme is robust against JPEG compression and common image attacks with the watermark logo being restricted to 64 × 63 pixels for a 512 × 512 cover image because some blocks on the border cannot be used for embedding. Parah et al. [13] proposed a watermarking scheme based on inter-block coefficient differencing in DCT. They considered all blocks and made use of the coefficient differences for embedding. This scheme can use 64 × 64 watermark for 512 × 512 image and is robust against various attacks. However, it does not consider the correlation between upper and lower blocks and the quantized factor is fixed to each block coefficient. Consequently, the scheme would be vulnerable to multiple attacks.

最近，已經開發了幾種加水印的方法。 Golabi 等。文獻[5]提出了一種基於激進矩特徵的水印方法。該方法對旋轉和縮放攻擊具有魯棒性。但是，基於矩的技術無法抵抗裁剪攻擊。此外，總水印位只能嵌入到 127×512×512 的封面圖像中。 Patra 等。 [14]提出了一種基於中國餘數定理（CRT）的 DCT 水印方案。在該方案中，將主圖像劃分為 8×8 像素塊，選擇一個塊，然後隨機應用 DCT。然後，選擇水印位和 DCT 係數，並使用 CRT 根據幾種條件來計算修改量。該方案具有較低的計算複雜度，並且對常見的圖像處理攻擊具有魯棒性。該方案可抵抗 10％的種植攻擊。但是，尚未針對 25％的種植攻擊進行過測試。 Das 等。 [2]提出了一種基於 DCT 中塊間係數相關性的水印方案。他們僅基於預定義的閾值更改每個塊中的一個係數。這種方案對於 JPEG 壓縮和普通圖像攻擊具有魯棒性，對於 512×512 的封面圖像，水印徽標被限制為 64×63 像素，因為邊框上的某些塊無法用於嵌入。 Parah 等。 [13]提出了一種基於 DCT 中塊間係數差

異的水印方案。他們考慮了所有塊，並利用係數差進行嵌入。該方案可以對 512×512 圖像使用 64×64 水印，並且可以抵抗各種攻擊。但是，它不考慮上下塊之間的相關性，並且量化因子固定於每個塊係數。因此，該方案將容易受到多種攻擊。

H.-J. Ko, C.-T. Huang and G. Horng et al./Information Sciences 517 (2020) 128–147

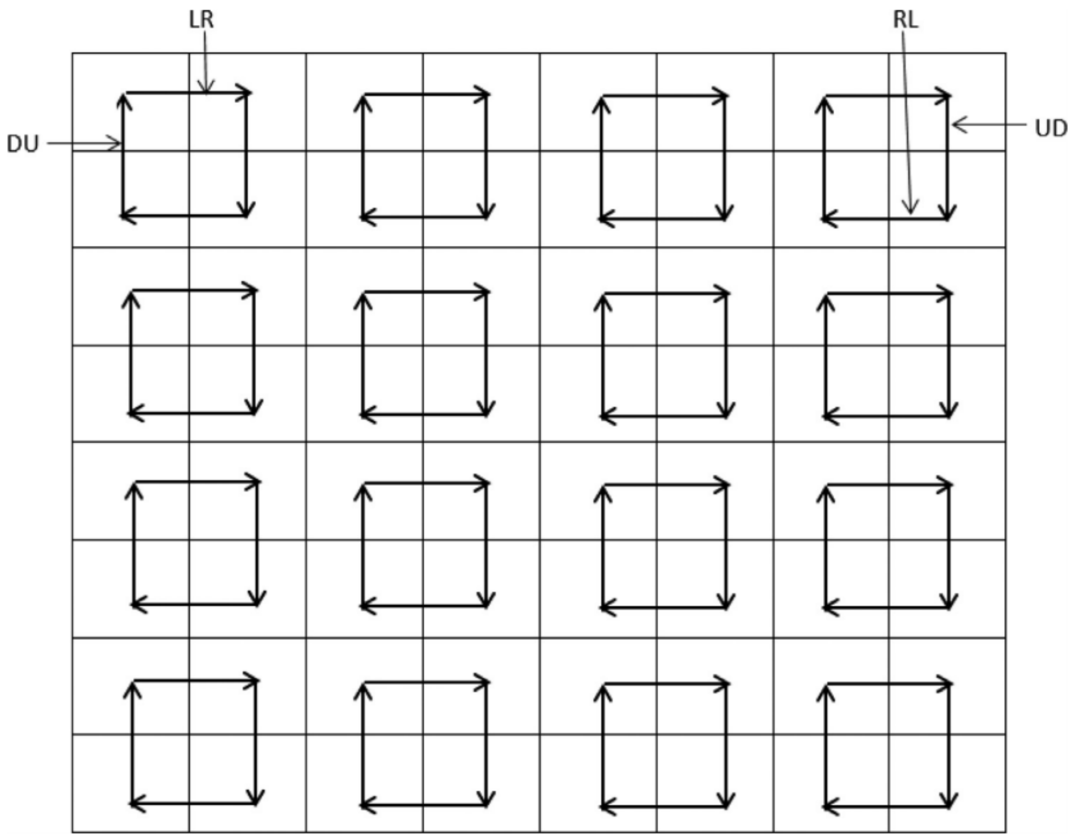


Fig. 2. Matrix of DCT blocks and Diff directions.

The proposed method is based on the methods proposed by Das et al. and Parah et al. and our contributions from this study are as follows:

(i) Herein, we present an innovative inter-block watermarking method suitable for gray and color images.

(ii) The requirements of robustness and transparency in digital watermarking methods are always a trade-off in applications. The robustness of the proposed method is increased than those in previous work while maintaining high transparency of the watermark in the image.

(iii) The proposed method is also robust against specific attacks, such as median filter after salt&pepper, five-degree rotation, and 25% cropping. Efficiency obtained in our experiments support the proposed method.

所提出的方法是基於 Das 等人提出的方法。 和 Parah 等。 我們對這項研究的貢獻如下：

（i）在此，我們提出一種適用於灰度和彩色圖像的創新的塊間水印方法。

（ii）數字水印方法對魯棒性和透明性的要求始終是應用程序的權衡。 所提出的方法的魯棒性比以前的工作有所提高，同時保持了圖像中水印的高透明度。

（iii）所提出的方法還可以抵抗特定的攻擊，例如鹽和胡椒後的中值濾波，五度旋轉和 25％的裁剪。 在我們的實驗中獲得的效率支持了所提出的方法。

The remainder of this paper is organized as follows. In Section 2, we will discuss the related works based on digital watermarking followed by the presentation of our proposed method in Section 3. We present the experimental results in Section 4, and the conclusions are outlined in Section 5.

本文的其餘部分安排如下。 在第 2 節中，我們將討論基於數字水印的相關工作，然後在第 3 節中介紹我們提出的方法。在第 4 節中介紹實驗結果，在第 5 節中概述結論。

2. Related work

DCT is widely used in watermarking methods that features energy compaction property. An image can be transformed into a frequency band by DCT, which can then be inverted to the original image.

DCT 被廣泛用於具有能量壓縮特性的水印方法。 可以通過 DCT 將圖像轉換為頻帶，然後將其反轉為原始圖像。

After the DCT process, the image pixels are transformed into coefficients. The first coefficient in the upper left corner of the array basis function is the direct current (DC) coefficient, whereas the remainder of the coefficients is the alternating current (AC) coefficients. AC is the most important part of an image, and any changes to AC will damage the image dramatically. On the contrary, minor changes in the image do not significantly change AC.
在 DCT 處理之後，圖像像素被轉換成係數。 數組基函數左上角的第一個係數是直流（DC）係數，而其餘的係數是交流（AC）係數。 交流電是圖像中最重要的部分，對交流電的任何更改都會嚴重損壞圖像。 相反，圖像的微小變化不會顯著改變 AC。
Das et al. [2] proposed a method based on inter-block DCT coefficient correlation, wherein two DCT coefficients of blocks are used to embed a watermark. Due to the inter-block correlation, coefficients at the same position in a neighboring block are similar and coefficients are modified by calculating the difference between neighboring blocks. Their method is robust against JPEG compression, cropping attacks, and various attacks. However, this method does not use border blocks, i.e., only a 64 × 63 watermark logo can be embedded into a 512 × 512 cover image.
Das 等。 [2]提出了一種基於塊間 DCT 係數相關性的方法，其中塊的兩個 DCT 係數用於嵌入水印。 由於塊間相關性，相鄰塊中相同位置處的係數相似，並且通過計算相鄰塊之間的差來修改係數。 他們的方法對 JPEG 壓縮，裁剪攻擊和各種攻擊具有魯棒性。 但是，此方法不使用邊界塊，即僅 64×63 水印徽標可以嵌入 512×512 封面圖像中。
Parah et al. [13] proposed a watermarking method based on DCT coefficient differencing between blocks, which considers all blocks and exploits the coefficient correlation to embed a watermark. This method is similar to the method proposed by Das et al. The primary difference is that it exploits all border blocks; therefore, the size of the watermark can increase to 64 × 64. Das et al. chose a block and next block from top to bottom. Parah et al. used four types of transitions to compute block differences, i.e., left to right (LR), rightmost to down (RD), right to left (RL), and leftmost to down (LD)
Parah 等。 [13]提出了一種基於塊之間 DCT 係數差異的水印方法，該方法考慮了所有塊並利用係數相關性來嵌入水印。 該方法類似於 Das 等人提出的方法。 主要區別在於它利用了所有邊界塊。 因此，水印的大小可以增加到 64×64。 從上到下選擇一個塊和下一個塊。 Parah 等。 使用四種類型的轉換來計算塊差異，即從左到右（LR），最右到下（RD），右到左（RL）和最左到下（LD）

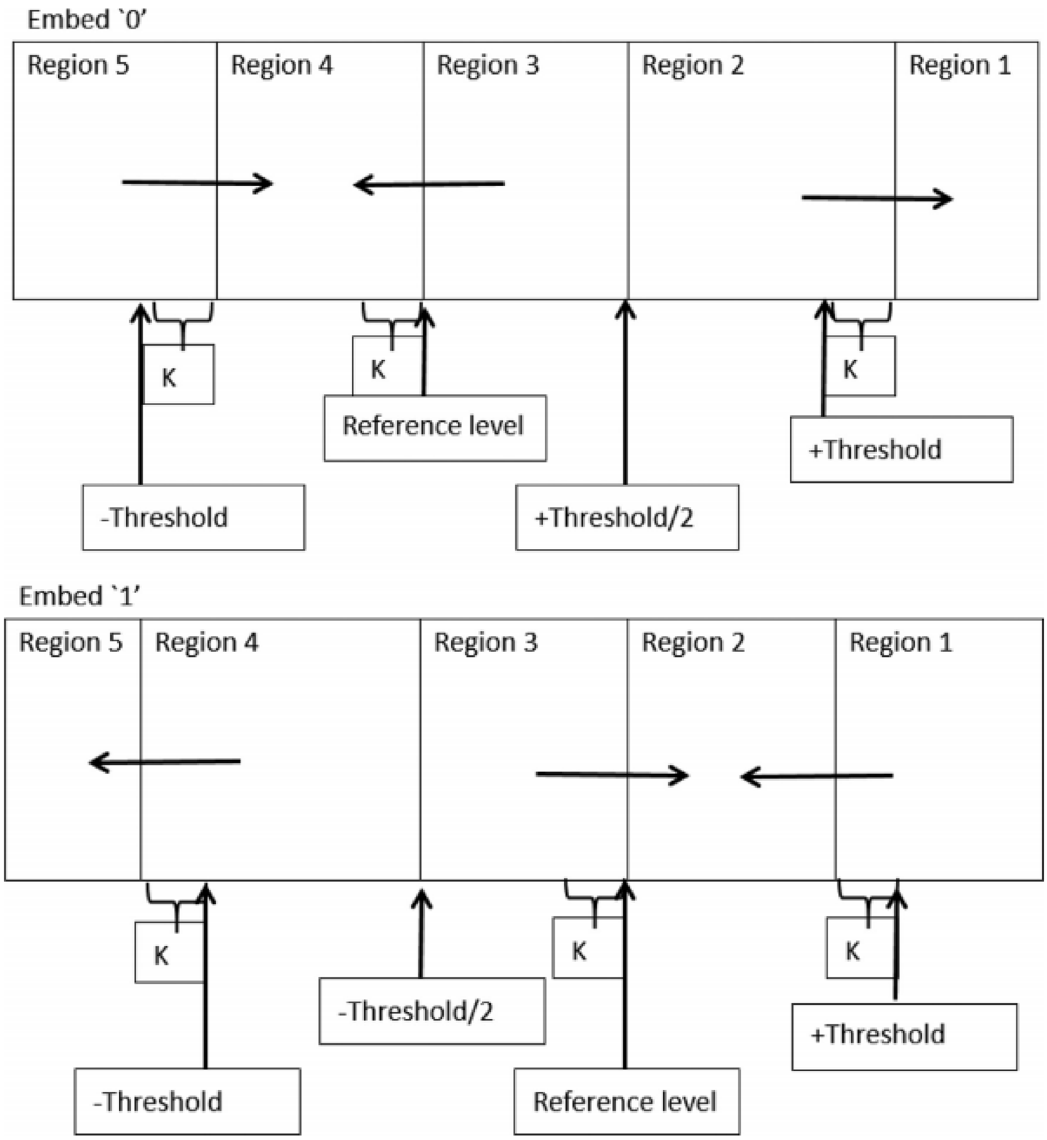


Fig. 3. Modification of coefficient $B_{P,Q}(x, y)$ for embedding a watermark bit.

27	27	27	30	30	28	30	31
27	27	27	30	30	28	30	31
27	27	27	30	30	28	30	31
27	27	27	30	30	28	30	31
27	27	27	30	30	28	30	31
23	23	23	26	29	28	28	28
27	27	27	28	29	30	28	25
21	21	21	25	27	26	25	26

32	30	30	28	26	29	28	24
32	30	30	28	26	29	28	24
32	30	30	28	26	29	28	24
32	30	30	28	26	29	28	24
32	30	30	28	26	29	28	24
29	28	25	26	24	23	24	24
28	29	27	28	25	24	24	21
27	29	30	26	23	22	21	21

Fig. 4. First two 8×8 blocks.

Both the methods proposed by Das et al. and Parah et al. are based on the inter-block of the image. Owing to the characteristic of blocks, the coefficients are close in the neighboring block. When the difference is used as the key of the embedding method, we do not need to alter the coefficients much for the embedding. A crucial difference the methods proposed by Das et al. and Parah et al. is the choice of the block directions. The method proposed by Das et al. uses the blocks from LR only, whereas that by Parah et al. uses the blocks from LR, RL, and up-to-down. Based on the method proposed by Parah et al., we see that different rules for choosing the blocks improve the robustness of watermarking an image

Das 等人提出的兩種方法。 和 Parah 等。 基於圖像的塊間。 由於塊的特性，在相鄰塊中係數接近。 當將差異用作嵌入方法的關鍵時，我們無需為嵌入而對係數進行太多更改。 Das 等人提出的方法的關鍵區別。 和 Parah 等。 是塊方向的選擇。 Das 等人提出的方法。 僅使用 LR 中的塊，而 Parah 等人使用。 使用 LR，RL 和 up-to-down 的塊。 基於 Parah 等人提出的方法，我們看到選擇塊的不同規則提高了對圖像加水印的魯棒性

221.375	−10.504	−3.44614	0.456732	4.625	0.081887	−2.76683	−0.11579
10.07196	0.544678	2.21836	**−3.27258**	1.519284	0.723164	−1.07797	0.301621
−5.32673	0.096674	−1.06694	1.203988	−0.47355	−0.27296	0.515165	−0.34238
1.460663	−0.11247	−0.03579	0.695283	−0.65715	−0.0314	0.052154	0.308864
−0.875	−0.92187	0.529589	−1.3906	1.375	−0.05295	−0.35466	−0.1615
2.930355	2.410806	−0.38306	0.8−82818	−1.49144	0.40827	0.346334	−0.03925
−4.69385	−3.12398	0.015165	−0.03362	1.143243	−0.65939	−0.18306	0.170798
3.660273	2.215834	0.13679	−0.29639	−0.58994	0.507745	0.049644	−0.14823

217.875	16.41321	1.238913	2.705284	−4.875	4.281523	0.704516	−1.12657
10.2984	−2.22929	1.292973	**3.868975**	−2.0638	2.126644	1.696832	0.09173
−4.37002	1.981532	−1.4205	−2.37505	−0.01161	−0.99768	−0.13128	0.227631
−0.76979	−1.51817	1.137009	0.991945	1.612268	0.044678	−1.2394	−0.50157
2.125	0.886592	−0.2822	−0.43404	−1.625	0.160993	1.605182	0.558701
−0.06335	−0.26099	−0.77796	0.648232	0.325602	0.275822	−1.00482	−0.40205
−2.38415	−0.13814	1.368718	−0.96524	0.951901	−0.72631	0.170495	0.179447
2.430825	0.195283	−1.0464	0.757239	−1.04776	0.631538	0.187737	−0.03848

Fig. 5. First two 8×8 blocks after DCT.

(a) Embedded watermark (b) Lena (c) Airplane (d) Pepper

Fig. 6. Embedded watermark and three cover images: (a) Lena, (b) Airplane, and (c) Pepper.

3. Proposed method

The proposed method is based on inter-block DCT coefficient correlation, wherein the difference in the same position of two adjacent DCT blocks is exploited and the amount of modification of the coefficients is determined by the watermark bit. 所提出的方法基於塊間 DCT 係數相關性，其中，利用兩個相鄰 DCT 塊的相同位置的差異，並且係數的修改量由水印位確定。

3.1. Preliminary phase

In the preliminary phase, each pixel in the original image is in the range 0–255 (8 bits per pixel). Each pixel value is subtracted by 128, such that the pixel values are in the range −128–127. Then, we divide the image into non-overlapping blocks, and DCT is performed for each block. The operations of the preliminary phase are described as follows.

Step 1. Each pixel value of the original image O is subtracted by 128.

Step 2. Input image O of size W × H is divided into non-overlapping 8 × 8 pixel blocks, resulting in R × C blocks (R = W/8 and C = H/8).

Step 3. Perform DCT for each block. The matrix of DCT blocks is BP,Q, where 1 ≤ P ≤ R and 1 ≤ Q ≤ C.

Step 4. Permute the watermark using a random bit named key.

在初步階段，原始圖像中的每個像素的範圍為 0-255（每個像素 8 位）。 每個像素值都減去 128，這樣像素值在-128–127 範圍內。 然後，我們將圖像劃分為非重疊塊，並對每個塊執行 DCT。 預備階段的操作描述如下。

步驟 1.將原始圖像 O 的每個像素值減去 128。

步驟 2.將尺寸為 W×H 的輸入圖像 O 劃分為不重疊的 8×8 像素塊，從而得到 R×C 塊（R = W / 8 和 C = H / 8）。

步驟 3.對每個塊執行 DCT。 DCT 塊的矩陣為 BP，Q，其中 1≤P≤R 和 1≤Q≤C.

步驟 4.使用名為 key 的隨機位對水印進行置換。

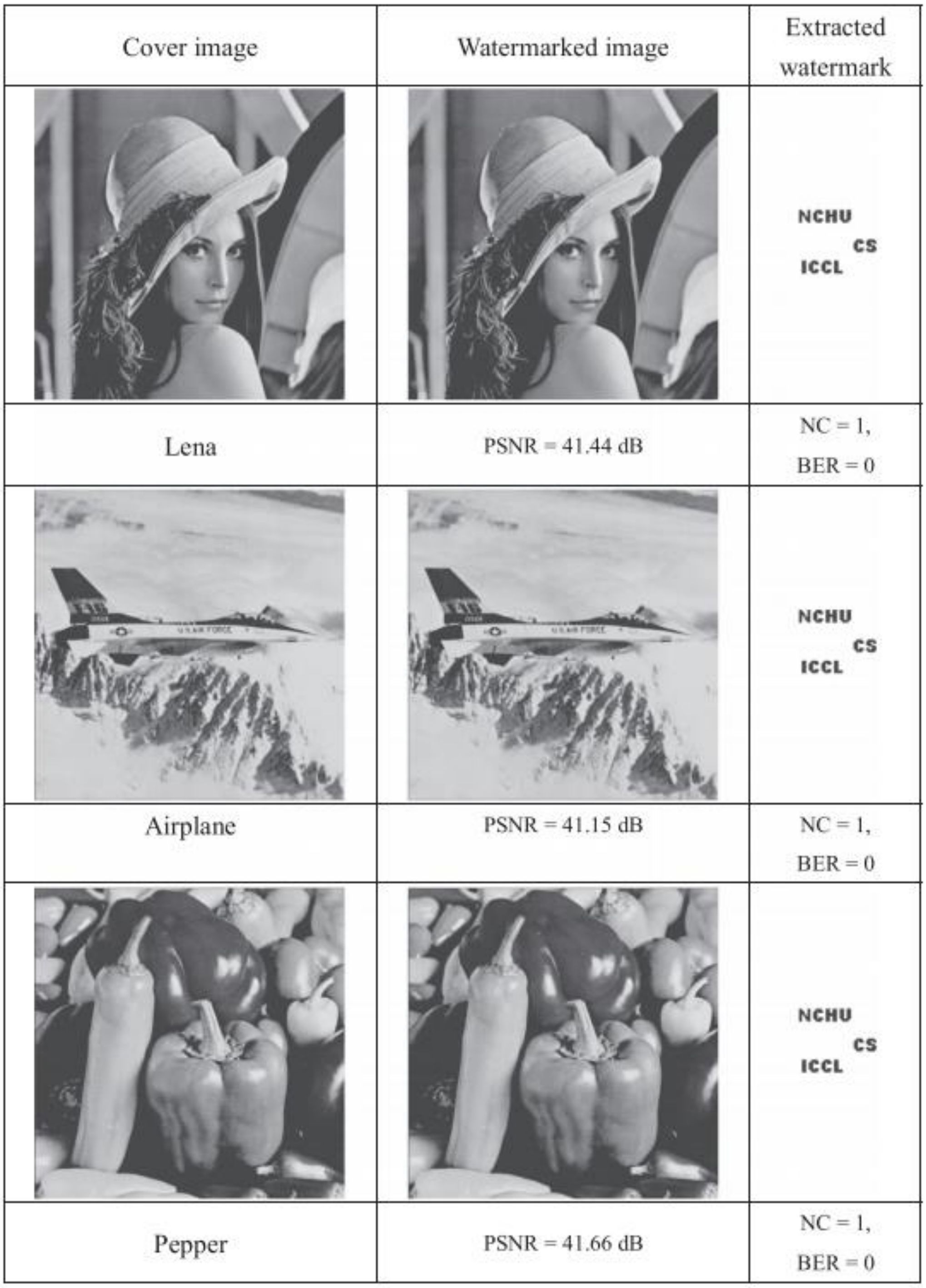


Fig. 7. Experimental results.

The coefficient of the 8 × 8 block is denoted as BP,Q(x, y), where 1 ≤ x, y ≤ 8, x is the index of blocks traversing from the top to bottom, and y is the index of blocks traversing from left to right. Therefore, the DC coefficient of the block is represented as BP,Q (1, 1). DC and remaining nine coefficients ordered by a zig-zag sequence are considered as low frequency band, which is a critical part of the images; therefore, any modification is not supposed to be in the low frequency band. On the contrary, the first nine low frequency zig-zag sequence-ordered AC coefficients are also robust to obstruct various attacks. Based on the characteristic of frequency domain, the middle frequency band is always the best part for embedding a watermark. Fig. 1 shows this zig-zag sequence ordering for DCT coefficients, including DC and frequency bands.

8×8 塊的係數表示為 BP，Q（x，y），其中 1≤x，y≤8，x 是從上到下遍歷的塊的索引，y 是從上到下遍歷的塊的索引 從左到右。 因此，該塊的 DC 係數被表示為 BP，Q（1，1）。 DC 和按鋸齒形順序排序的其餘九個係數被視為低頻帶，這是圖像的關鍵部分； 因此，任何修改都不應該在低頻段進行。 相反，前九個低頻 Z 字形序列排序的 AC 係數也很健壯，可以阻止各種攻擊。 根據頻域的特性，中頻帶始終是嵌入水印的最佳部分。 圖 1 顯示了 DCT 係數（包括 DC 和頻帶）的 Z 字形序列排序。

3.2. Watermark embedding phase

To embed the watermark bits in the DCT blocks, we calculate the difference between the DCT coefficients of the adjacent blocks. The difference is denoted as "Diff." Note that are four types of transitions, namely LR, RD, DU, and RL. Fig. 2 shows the four directions of the DCT block matrix. The four transitions for "Diff" include the following:

為了將水印位嵌入 DCT 塊中，我們計算相鄰塊的 DCT 係數之間的差。 差異稱為"差異"。 請注意，有四種類型的過渡，即 LR，RD，DU 和 RL。 圖 2 示出了 DCT 塊矩陣的四個方向。 "差異"的四個過渡包括：

LR:

$$Diff = B_{P,Q}(x, y) - B_{P,Q+1}(x, y), \tag{1}$$

UD:

$$Diff = B_{P,Q}(x, y) - B_{P+1,Q}(x, y), \tag{2}$$

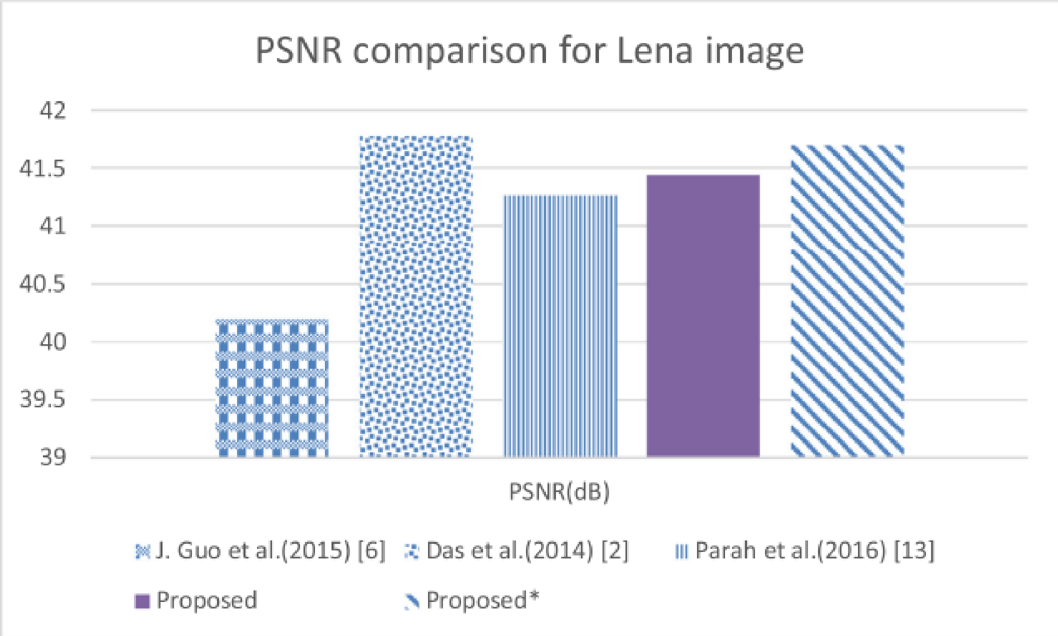


Fig. 8. PSNR comparison for Lena image.

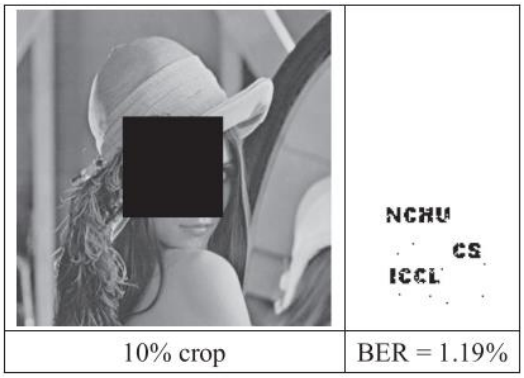


Fig. 9. 10% center cropped Lena image with BER = 1.19%.

DU:

$$Diff = B_{P,Q}(x,y) - B_{P-1,Q}(x,y), \text{ and} \tag{3}$$

RL:

$$Diff = B_{P,Q}(x,y) - B_{P,Q-1}(x,y). \tag{4}$$

Note that the two coefficients may differ significantly; therefore, large modifications can change the image dramatically. Therefore, we divide the Diff range into five regions, as shown in Fig. 3. The actual Diff level is shifted by K from the level boundary after compression. Then, the difference of the coefficients around the boundary can be modified easily to be extracted as 0 rather than 1 and vice versa. A greater K value will result in more robust watermarking with degraded image quality. Herein, the amount of coefficients changes depend on the characteristics of DCT blocks.
請注意，這兩個係數可能存在顯著差異。 因此，大的修改可以極大地改變圖像。 因此，我們將 Diff 範圍劃分為五個區域，如圖 3 所示。壓縮後，實際 Diff 級別從級別邊界偏移了 K。 然後，可以容易地修改邊界周圍的係數差，以將其提取為 0 而不是 1，反之亦然。 較大的 K 值將導致水印效果更強健，圖像質量下降。 這裡，係數變化量取決於 DCT 塊的特性。

Embedding bit 1
If Diff belongs to region 1 or 3, the coefficient BP,Q(x, y) is modified to shift the Diff to region 2. If Diff belongs to region 5, the modified coefficient shifts Diff to region 4
嵌入位 1
如果 Diff 屬於區域 1 或 3，則將係數 BP，Q（x，y）修改為將 Diff 移至區域 2。如果 Diff 屬於區域 5，則修改後的係數會將 Diff 移至區域 4。
Embedding bit 0
If Diff belongs to region 3 or 5, the BP,Q (x, y) is modified to shift the Diff to region 4. If Diff belongs to region 2, the BP,Q (x, y) is modified to shift the Diff to region 1.
嵌入位 0
如果 Diff 屬於區域 3 或 5，則將 BP，Q（x，y）修改為將 Diff 移至區域 4。如果 Diff 屬於區域 2，則將 BP，Q（x，y）修改為將 Diff 移位。 到區域 1。

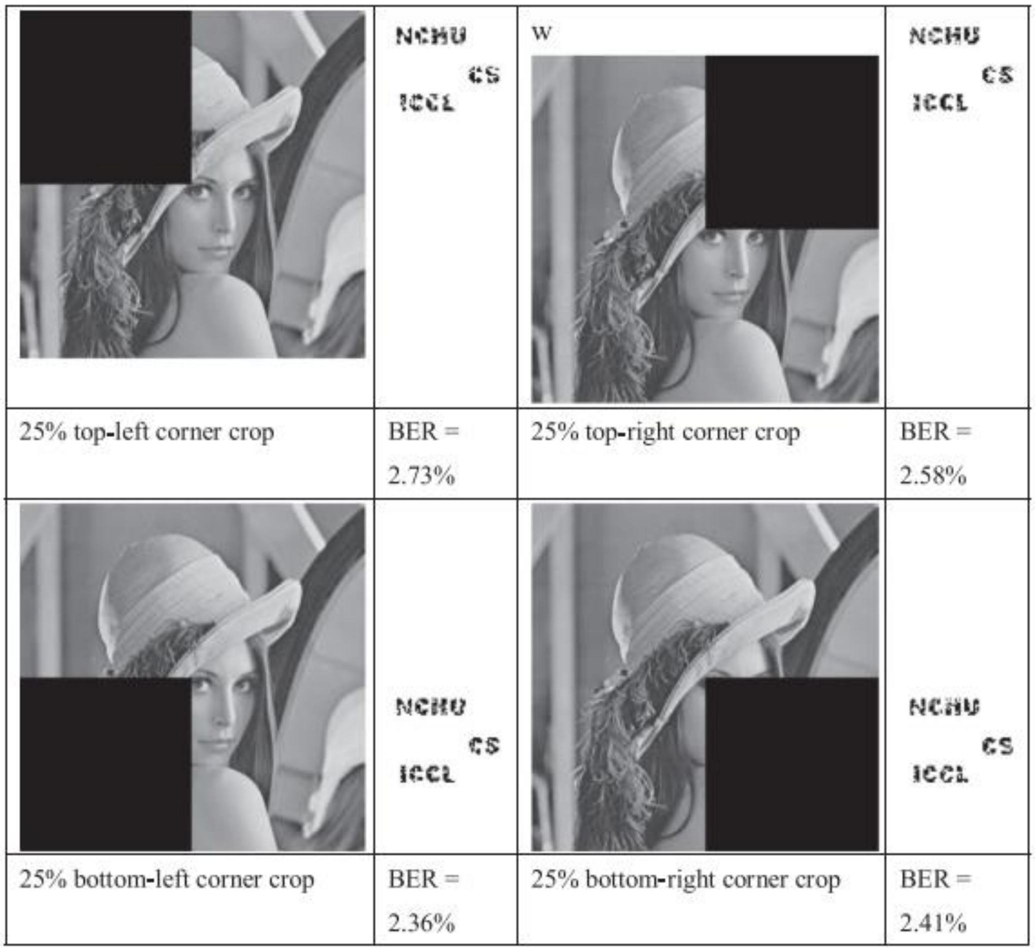


Fig. 10. 25% cropped Lena images in four different regions (average BER = 2.52%).

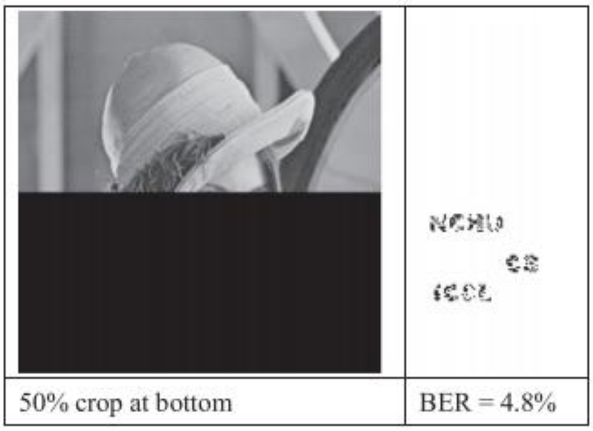


Fig. 11. 50% bottom cropped Lena image (BER = 4.8%).

The coefficients are modified successively, and the amount of change, i.e., addition or subtraction of coefficients, is given as follows:
係數被連續修改，並且變化量，即係數的加法或減法給出如下：

$$M(B_{P,Q}) = Z \times \frac{DC(B_{P,Q}) - Med(B_{P,Q})}{DC(B_{P,Q})} \tag{5}$$

where M(BP,Q) represents the modification parameter of block BP,Q, DC(BP,Q) is DC coefficient of block BP,Q, and Med(BP,Q) is the median value of first nine low frequency zig-zag-ordered AC coefficients of block BP,Q. However, if the absolute value of the median exceeds that of the DC coefficient, the median would be replaced by the DC coefficient, i.e., Med = DC, if abs(Med(BP,Q)) > abs(DC(BP,Q)). Eq. (5) is replaced with P(BP,Q) = Z × Med (BP,Q) for a DC coefficient value greater than 1000 or less than 1. Herein, Z is a scaling variable. A high Z value will result in a robust watermark against attacks but will reduce the quality of the watermarked image.
其中 M(BP,Q)表示塊 BP，Q 的修改參數，DC（BP，Q）是塊 BP，Q 的 DC 係數，Med（BP，Q）是前九個低頻 Zig-的中值 塊 BP，Q 的 Zag 排序 AC 係數。 但是，如果中位數的絕對值超過 DC 係數的絕對值，則如果 abs（Med（BP，Q））> abs（DC（BP，Q），則中位數將由 DC 係數代替，即 Med = DC ））。 等式 對於大於 1000 或小於 1 的 DC 係數值，將（5）替換為 P（BP，Q）= Z×Med（BP，Q）。這裡，Z 是縮放變量。 高 Z 值會導致強大的水印抵禦攻擊，但會降低水印圖像的質量。

The process of watermark embedding is described as follows.
水印嵌入的過程描述如下。

Step 1. Compute median value of the first nine low frequency zig-zag ordered AC coefficients of block $B_{P,Q}$ as *Med*.
Step 2. Compute the absolute value of $DC(B_{P,Q})$ denoted as $abs(DC(B_{P,Q}))$.
If $abs(DC(B_{P,Q}))>1000$ or $abs(DC(B_{P,Q}))<1$; then,
$M(B_{P,Q})=Z \times Med(B_{P,Q})$
Else
$M(B_{P,Q})=Z \times (DC(B_{P,Q})\text{-}Med(B_{P,Q}))/DC(B_{P,Q}))$
End if
Step 3. Follow Eqs. (1)–(4) and compute *Diff*; coefficient $B_{P,Q}(x, y)$ is modified until the *Diff* is shifted to the predefined region.
If Embed $W_i = 1$ **then**
IF $Diff > Th\text{-}K$ **then**
While $Diff > Th\text{-}K$
$B_{P,Q}(x, y) = B_{P,Q}(x, y) - M(B_{P,Q})$
End While
Else If $(Diff < K)$ && $(Diff > \text{-}Th/2)$
While $Diff < K$
$B_{P,Q}(x, y) = B_{P,Q}(x, y) + M(B_{P,Q})$
End While
Else If $Diff < \text{-}Th/2$
While $Diff > \text{-}Th\text{-}K$
$B_{P,Q}(x, y) = B_{P,Q}(x, y) - M(B_{P,Q})$
End While
END IF
Else Embed $W_i=0$ **then**
IF $Diff > Th/2$ **then**
While $\text{-}Diff > Th+K$
$B_{P,Q}(x, y) = B_{P,Q}(x, y) + M(B_{P,Q})$
End While
Else If $(Diff > \text{-} K)$ && $(Diff < Th/2)$
While $\text{-}Diff < \text{-}K$
$B_{P,Q}(x, y) = B_{P,Q}(x, y) \text{ -}M(B_{P,Q})$
End While
Else If $Diff < K\text{-}Th$
While $\text{-}Diff > \text{-}Th+K$
$B_{P,Q}(x, y) = B_{P,Q}(x, y) + M(B_{P,Q})$
End While
END IF
Step 4. Apply Inverse DCT to each block
Step 5. Add 128 to pixel values

In our experiments, threshold, *K*, *Reference level*, and *Z* was set to 80, 12, 0, and 2, respectively.

3.3. Watermark embedded for color images

To embed a watermark into the color image, red, green, and blue planes of the image should be separated first. Then, we embed the watermark bits in each plane following the watermark embedding phase. Note that we share the same watermark and key in each plane.

要將水印嵌入彩色圖像中，應首先分離圖像的紅色，綠色和藍色平面。 然後，在水印嵌入階段之後，將水印位嵌入每個平面中。 請注意，我們在每個平面中共享相同的水印和密鑰。

3.4. Watermark extraction

An authorized user can confirm the copyright of the watermarked image by watermark extraction and recovering the watermarked image as an original-like image after receiving the watermarked image from the sender. Watermark extraction requires a watermarked image and initial permutation order of the binary watermark.

授權用戶可以通過提取水印並在從發送者接收到水印圖像之後將水印圖像恢復為原始圖像來確認水印圖像的版權。 水印提取需要水印圖像和二進制水印的初始排列順序。

Step 1. The pixel values of watermarked image OE are subtracted by 128.
Step 2. Divide OE of size W × H into non-overlapping 8 × 8 pixel blocks, resulting in R × C blocks (R = W/8 and C = H/8)
Step 3. DCT is performed for each block, and DCT blocks are denoted as BP,Q, where 1 ≤ P ≤ R and 1 ≤ Q ≤ C
Step 4. Follow Eqs. (1)–(4) to compute Diff; K is set to zero; WMb is the extracted watermark
WMb = 0 if Diff falls in region 1 or 4
WMb = 1 if Diff falls in region 2 or 5
Step 5. Recover the extracted watermark using a pseudorandom key
步驟 1.將加水印圖像 OE 的像素值減去 128。
步驟 2.將大小為 W×H 的 OE 劃分為不重疊的 8×8 像素塊，得到 R×C 塊（R = W / 8 和 C = H / 8）
步驟 3.對每個塊執行 DCT，並將 DCT 塊表示為 BP，Q，其中 1≤P≤R 和 1≤Q≤C
步驟 4.按照方程式。（1）–（4）計算差值； K 設置為零； WMb 是提取的水印
如果 Diff 落在區域 1 或 4 中，則 WMb = 0
如果 Diff 落在區域 2 或 5 中，則 WMb = 1
步驟 5.使用偽隨機密鑰恢復提取的水印

3.5. Example of the proposed embedding/extraction method
Herein, we describe an example of watermark embedding. We assume scaling variable Z as 2, where the threshold (Th) value is 80 and K is 0. Fig. 4 shows the first two 8 × 8 blocks, and Fig. 5 shows the same blocks after applying DCT.
在此，我們描述水印嵌入的示例。 我們假定縮放變量 Z 為 2，其中閾值（Th）值為 80，K 為 0。圖 4 顯示了前兩個 8×8 塊，圖 5 顯示了應用 DCT 之後的相同塊。

In this example, the median of nine AC coefficients in zig-zag order is 0.456732 and DC value is 221.375. As a result, M is 1.995874. We assume that the watermark bit is 1 and target AC coefficient is B(2,4). Herein, Diff would be −7.14156. Therefore, the value −3.27258 must add 1.9958874 iteratively until Diff is greater than K, thereby the new value is 4.707695.
在此示例中，九個 AC 係數的 Z 字形順序的中位數為 0.456732，DC 值為 221.375。 結果，M 為 1.999574。 我們假設水印位為 1，目標 AC 係數為 B（2,4）。 在此，Diff 將為-7.14156。 因此，值-3.27258 必須迭代添加 1.9958874，直到 Diff 大於 K，從而新的值為 4.707695。

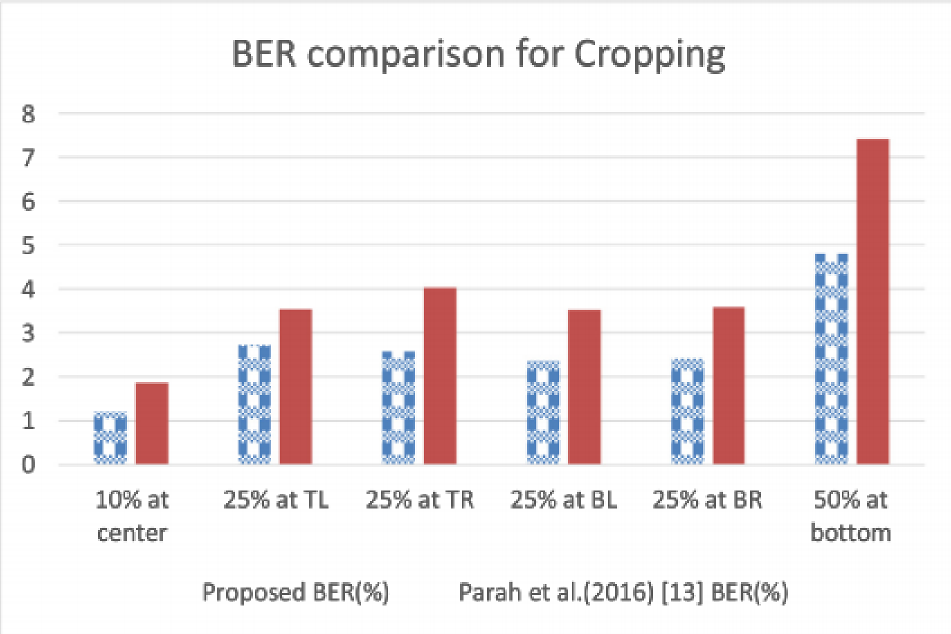


Fig. 12. BER comparison of different cropping methods.

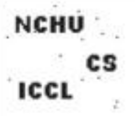
			
(a) 1° rotation	BER = 0.39%	(b) 5° rotation	BER = 1.78%
			
(c) 45° rotation	BER = 4.85%		

Fig. 13. Watermarked images and extracted watermark after 1°, 5°, and 45° rotation attacks.

When we need to extract the watermark, we already know that B(2,4) is our target. Herein, B(2,4) is 4.707695, the same position of the next block is 3.868975, and Diff is 0.83912. According to the proposed method, the value 0.83912 falls in region 2; therefore, we can extract the watermark bit as 1.

當我們需要提取水印時，我們已經知道 B（2,4）是我們的目標。 在此，B（2，4）為 4.707695，下一個塊的相同位置為 3.868975，差為 0.83912。 根據提出的方法，值 0.83912 落在區域 2 中； 因此，我們可以將水印位提取為 1。

4. Experimental results and discussions

The proposed method was tested using various attacks. Fig. 6 shows the embedded watermark and three cover images, i.e., Lena, Airplane, and Pepper images. Each cover image is 512 × 512 and size of watermark is 64 × 64.

使用各種攻擊對提出的方法進行了測試。 圖 6 示出了嵌入的水印和三個封面圖像，即 Lena，飛機和 Pepper 圖像。 每個封面圖像為 512×512，水印大小為 64×64。

H.-J. Ko, C.-T. Huang and G. Horng et al. / Information Sciences 517 (2020) 128–147

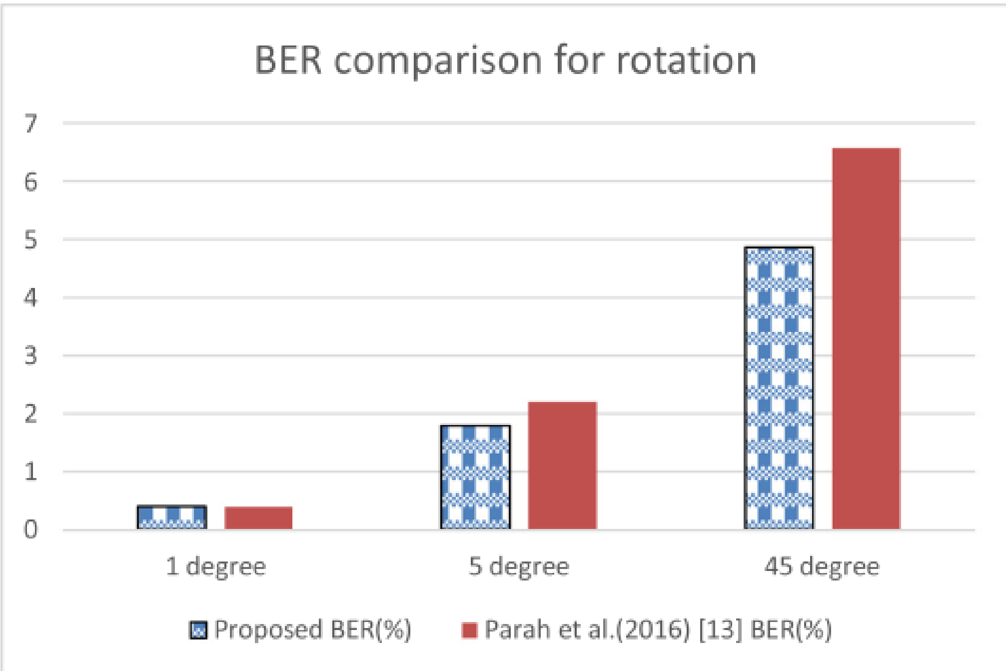


Fig. 14. BER comparison for three rotation degrees.

We evaluate the quality of the watermarked image with the peak signal-to-noise ratio (PSNR). For the extracted watermark, we apply the normalized cross-correlation (NC) and bit error rate (BER) as benchmarks. PSNR, NC, and BER are defined as follows.
我們使用峰值信噪比（PSNR）評估水印圖像的質量。 對於提取的水印，我們應用歸一化互相關（NC）和誤碼率（BER）作為基準。 PSNR，NC 和 BER 定義如下。
Peak signal-to-noise ratio: PSNR is most commonly used to evaluate the quality of a watermarked image with respect to the original image. PNSR is given as follows:
峰值信噪比：PSNR 最常用於評估水印圖像相對於原始圖像的質量。 PNSR 給出如下：

$$PSNR(dB) = 10\log_{10}\frac{255^2}{MSE} \tag{6}$$

Mean square error (MSE) is defined as follows:

$$\mathrm{MSE} = \frac{1}{W \times H}\sum_{i=0}^{W}\sum_{j=1}^{H}\left[I(i,j) - I_w(i,j)^2\right], \tag{7}$$

where W and H are width and height of the image, respectively, I(i,j) is the original pixel value, and Iw(i,j) is the pixel value of the watermarked image. PSNR value evaluates the imperceptibility of the watermarked image. Therefore, the PSNR value is supposed to be as high as possible.
其中 W 和 H 分別是圖像的寬度和高度，I（i，j）是原始像素值，而 Iw（i，j）是加水印圖像的像素值。 PSNR 值可評估水印圖像的不可感知性。因此，假定 PSNR 值盡可能高。

Normalized cross-correlation: The NC is used to evaluate the watermark. NC is defined as follows:

$$NC = \frac{\sum_i\sum_j W(i,j) \times W_x(i,j)}{\sum_i\sum_j [W(i,j)]^2}, \tag{8}$$

where W is the original watermark bit, Wx is the extracted watermark bit, and (i,j) is the position of the watermark. Greater NC values indicate good quality for an extracted watermark.
其中 W 是原始水印位，Wx 是提取的水印位，而（i，j）是水印的位置。較高的 NC 值表示提取的水印質量良好。
Bit error rate: BER is used to evaluate the amount of error bits between a watermark and extracted watermark. The method is robust against attacks if the BER value is 0. The lower BER value is better. BER is defined as follows:
誤碼率：BER 用於評估水印和提取的水印之間的誤碼量。 如果 BER 值為 0，則該方法對攻擊具有魯棒性。BER 值越低越好。 BER 定義如下：

$$BER(\%) = \frac{1}{n}\left[\sum_{j=1}^{n} B(j) \oplus B_x(j)\right] \times 100, \tag{9}$$

where n is the total amount of embedded watermark bits, B(j) is the original watermark bit, and Bx(j) is the bit of the extracted watermark.
其中 n 是嵌入水印位的總數，B（j）是原始水印位，而 Bx（j）是提取的水印位。
One evaluation benchmark, namely tamper assessment function (TAF), is used to assess the quality of the extracted watermark [2,14]. TAF is the same as BER, except the watermark is not in a binary format.
一種評估基準，即篡改評估功能（TAF），用於評估提取的水印的質量[2,14]。 除水印不是二進制格式外，TAF 與 BER 相同。

4.1. Watermark extraction without attack
Fig. 7 shows the cover images, watermarked images, and extracted watermarks. For all watermarked images, the watermarks can be extracted using the proposed method. Herein, all the PSNR values of the watermarked images are greater than 41 dB.
圖 7 示出了封面圖像，水印圖像和提取的水印。 對於所有帶水印的圖像，可以使用所提出的方法來提取水印。 在此，所有帶水印的圖像的 PSNR 值都大於 41dB。

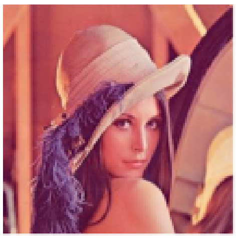
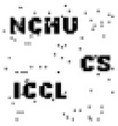
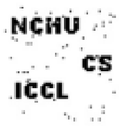
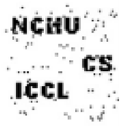
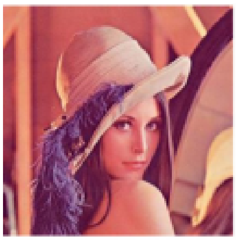
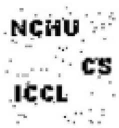
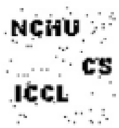
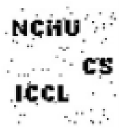
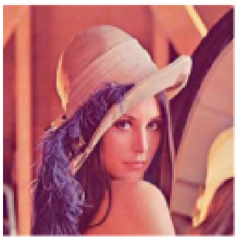
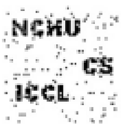
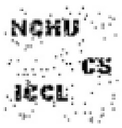
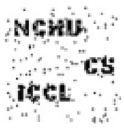
Compressed images Q:Compress ratio	Extracted watermark (red plane)	Extracted watermark (green plane)	Extracted watermark (blue plane)
			
Q = 90, PSNR = 37.85	BER = 1.76%, NC = 0.9814	BER = 1.46%, NC = 0.9845	BER = 2.31%, NC = 0.9767
			
Q = 70, PSNR = 36.29	BER = 1.80%, NC = 0.9809	BER = 1.80%, NC = 0.9819	BER = 1.85%, NC = 0.9803
			
Q = 30, PSNR = 34.7766	BER = 4.10%, NC = 0.9674	BER = 3.80%, NC = 0.9722	BER = 4.19%, NC = 0.9652

Fig. 15. The watermarked images after JPEG compression and extracted watermarks.

Fig. 8 shows a comparison between PSNR values for the Lena watermarked image obtained by the proposed method and those reported by Guo et al. [6], Das et al. [2], and Parah et al. [13]. Results indicate that the proposed method is better than previous methods, except Das et al. The PSNR obtained by Das et al. is slightly higher because the applied watermark is smaller. If we use the same watermark as the size of 64 × 63 bits from Das et al., then the proposed method achieves nearly the same PSNR as [2] with PSNR difference of only 0.08 dB, which is lower than that obtained by Das et al. This result is within 0.1 dB and proves the proposed method (designated as proposed∗ in our method of Fig. 8). 圖 8 顯示了通過該方法獲得的 Lena 水印圖像的 PSNR 值與 Guo 等報導的 PSNR 值之間的比較。 [6]，Das 等。 [2]，和 Parah 等。 [13]。 結果表明，除了 Das 等人，本文提出的方法優於以前的方法。 Das 等人獲得的 PSNR。 較高，因為應用的水印較小。 如果我們使用與 Das 等人的 64×63 位大小相同的水印，則所提出的方法可實現與[2]幾乎相同的 PSNR，而 PSNR 差異僅為 0.08 dB，這比 Das 等人獲得的更低。 等 該結果在 0.1 dB 以內，證明了所提出的方法（在我們的圖 8 方法中被指定為∗)。

4.2. Robustness analysis

4.2.1. Watermark extraction after cropping attacks

Fig. 9 shows a 10% crop at the image center. Herein, the BER of the extracted watermark is 1.19%. Fig. 10 shows 25% cropped (in different regions) Lena images with an average BER value of 2.52%. Fig. 11 shows a 50% bottom cropped Lena image with an average BER value 4.8%. Experimental results indicate that we can extract the watermark in all cases using the proposed method. A comparison between the proposed method and that proposed by Parah et al. [13] with a cropping operation (Lena image) is shown in Fig. 12. The proposed method has a lower BER value and is approximately improved by 32%.

圖 9 顯示了圖像中心的 10％裁剪。 在此，提取的水印的 BER 為 1.19％。 圖 10 顯示了 25％裁剪（在不同區域）的 Lena 圖像，平均 BER 值為 2.52％。 圖 11 顯示了 50％底部裁剪的 Lena 圖像，平均 BER 值為 4.8％。 實驗結果表明，使用該方法可以提取所有情況下的水印。 提出的方法與 Parah 等人提出的方法之間的比較。 [13]使用裁剪操作（Lena 圖像）顯示在圖 12 中。所提出的方法具有較低的 BER 值，大約可提高 32％。

4.2.2. Watermark extraction after rotation attacks

The watermarked image was tested by rotation attacks. Fig. 13 shows the extracted watermark after 1°, 5°, and 45° clockwise rotations. Herein, the watermark was extracted by rerotating the image in the counterclockwise direction. After the rotation attack, we can still extract a watermark with low BER. A comparison between the proposed method and that proposed by Parah et al. [13] is shown in Fig. 14. As can be seen, relative to a rotation attack, the proposed method outperforms the compared method with an approximate improvement by 23%.

通過旋轉攻擊測試了帶有水印的圖像。 圖 13 顯示了順時針旋轉 1°，5°和 45°後提取的水印。 在此，通過沿逆時針方向重新旋轉圖像來提取水印。 旋轉攻擊後，我們仍然可以提取低 BER 的水印。 提出的方法與 Parah 等人提出的方法之間的比較。 [13]在圖 14 中顯示。可以看出，相對於旋轉攻擊，所提出的方法以 23％的改進率優於比較方法。

4.2.3. Watermark extraction after JPEG compression

Herein, we test a watermarked image with different JPEG compression quality factors. Herein, the K value was set to 20 for robustness against JPEG compression, and we set Q as the compression ratio of the JPEG. Fig. 15 shows that color watermarked images after JPEG compression can still be used to extract a good quality watermark. Fig. 16 shows that the proposed method demonstrates lower BER values and is approximately improved by 25%.

在這裡，我們測試具有不同 JPEG 壓縮質量因子的水印圖像。 這裡，為了抵抗 JPEG 壓縮的魯棒性，將 K 值設置為 20，並且將 Q 設置為 JPEG 的壓縮率。 圖 15 顯示 JPEG 壓縮後的彩色水印圖像仍然可以用來提取高質量的水印。 圖 16 表明，所提出的方法具有較低的 BER 值，大約可提高 25％。

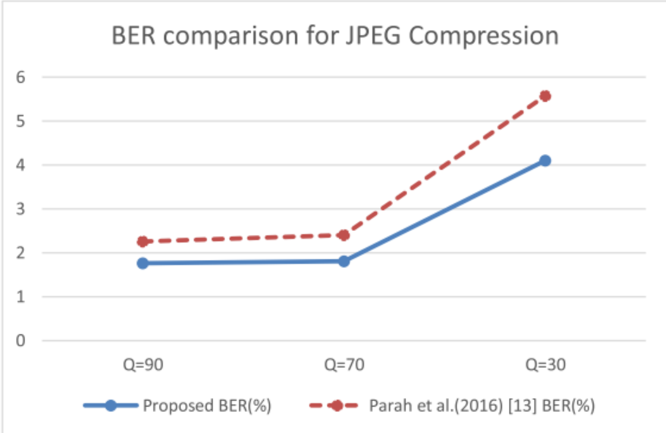


Fig. 16. BER comparison for JPEG at various compression levels.

(a) Watermarked image after salt&pepper noise	(b) Watermark extracted from (a)	(c) Watermarked image after Gaussian noise	(d) Watermark extracted from (c)

Fig. 17. Watermarks extracted after noise addition attacks: (a) watermarked image after salt&pepper noise, (b) BER of extracted watermark is 17.06%, (c) watermarked images after Gaussian noise, and (d) BER of extracted watermark is 9.98%.

4.2.4. Watermark extraction after various attacks

The proposed method was tested by noise addition, median filtering, histogram equalization, and sharpening. The detailed results for the various attacks are listed as follows:

通過噪聲添加，中值濾波，直方圖均衡和銳化測試了該方法。 各種攻擊的詳細結果如下：

• Noise addition: The watermarked image in Fig. 17(a) is distorted by adding salt&pepper noise, e.g., a noise density of 0.01, and the watermark is extracted after this attack, as shown in Fig. 17(b). The watermarked image in Fig. 17(c) is tested by adding Gaussian noise (mean = 0, variance = 0.001), and the watermark is extracted after this attack, as shown in Fig. 17(d).

•噪聲添加：通過添加鹽和胡椒噪聲（例如，噪聲密度 0.01）使圖 17（a）中的水印圖像失真，如圖 17（b）所示，在此攻擊之後提取水印。通過添加高斯噪聲（平均值= 0，方差= 0.001）來測試圖 17（c）中的水印圖像，並且在該攻擊之後提取水印，如圖 17（d）所示。

• Median filtering: Fig. 18(a) is filtered through 3 × 3 median filtering, and Fig. 18(b) shows the extracted watermark after the attack.
•中值濾波：圖 18（a）通過 3×3 中值濾波進行濾波，圖 18（b）顯示了攻擊後提取的水印。

• Histogram equalization: The watermarked image in Fig. 18(c) is processed through histogram equalization, and Fig. 18(d) presents the extracted watermark.
•直方圖均衡化：通過直方圖均衡化處理圖 18（c）中的水印圖像，圖 18（d）顯示提取的水印。

• Sharpening: Fig. 19 shows watermarked images and the watermarks extracted after applying a sharpening attack.
•銳化：圖 19 顯示了加水印的圖像和在應用銳化攻擊後提取的水印。

Experimental results of the proposed method compared to previous methods [2,13] are shown in Fig. 20, suggesting that proposed method outperforms the other methods, except for noise addition. The BER of proposed method after applying salt&pepper noise was 17.06, whereas that of the methods proposed by Parah et al. and Das et al. was 15.6 and 18.19, respectively. The BER of the proposed method was 9.9854 after Gaussian noise was applied, whereas that of the method proposed by Parah et al. was 8.66. The BER of the proposed method after median filtering was 7.64, whereas that of the method by proposed Parah et al. was 9.95. The BER of the proposed method after sharpening was 2.124, whereas that of the method proposed by Parah et al. was 2.98. Upon comparing the proposed method to that proposed by Parah et al., a better PSNR is significantly promoted and higher BER is evaluated, as listed in Table 1.
與之前的方法[2,13]相比，該方法的實驗結果如圖 20 所示，這表明該方法比添加噪聲的方法要優於其他方法。 施加鹽和胡椒噪聲後，該方法的誤碼率是 17.06，而 Parah 等人提出的方法的誤碼率是。 和 Das 等。 分別是 15.6 和 18.19。 應用高斯噪聲後，該方法的 BER 為 9.9854，而 Parah 等人的方法的 BER 為 9.9854。 是 8.66。 提出的方法在中值濾波後的 BER 為 7.64，而提出的 Parah 等人的方法的 BER。 是 9.95。 銳化後提出的方法的 BER 為 2.124，而 Parah 等人提出的方法的 BER。 是 2.98。 通過將所提出的方法與 Parah 等人提出的方法進行比較，可以顯著提高更好的 PSNR 並評估更高的 BER，如表 1 所示。

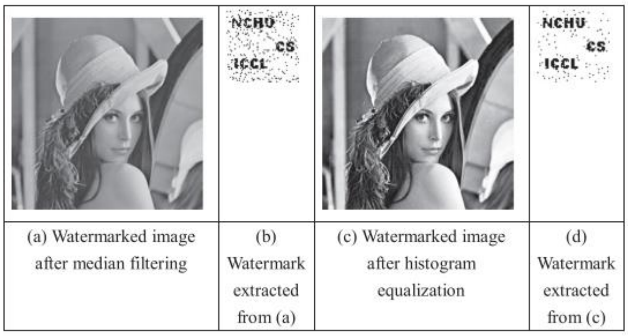


Fig. 18. Watermarks extracted after median filtering and histogram equalization attacks: (a) watermarked image with median filtering, (b) BER of extracted watermark is 7.64%, (c) watermarked images after histogram equalization, and (d) BER of extracted watermark is 2.97%.

Fig. 19. Watermark extracted after sharpening: (a) watermarked image after sharpening and (b) BER of extracted watermark is 1.92%.

Table 1
Comparisons for a variety of attacks.

	Proposed method			Parah et al. 2016 [13]		
Attack	PSNR	BER(%)	NC	PSNR	BER(%)	NC
Median Filter(3×3)	37.18	**7.64**	0.9258	33.52	9.95	0.9445
salt and pepper noise (0.01)	25.36	**17.06**	0.8299	24.9	15.6	0.8598
Gaussian noise(var $= 0.001$)	20.69	**9.98**	0.9035	20.69	8.66	0.9375
Histogram equalization	18.8	**2.97**	0.9719	11	3.87	0.9665
Sharpening	30.03	**1.92**	0.9807	25.69	2.98	0.9731

4.2.5. Watermark extraction after combined attacks

The proposed method was also tested by combined attacks. The results are listed as follows:

聯合攻擊還對提出的方法進行了測試。 結果如下：

• Salt&pepper noise and median filtering: The results obtained by adding salt&pepper noise, e.g., a noise density of 0.01, to the watermarked image and then filtering through 3 × 3 median filtering are shown in Fig. 21(a), and the extracted watermark is shown in Fig. 21(b).

•椒鹽噪聲和中值濾波：將椒鹽噪聲（例如，噪聲密度為 0.01）添加到水印圖像上，然後通過 3×3 中值濾波進行濾波的結果如圖 21（a）所示，並提取水印 如圖 21（b）所示。

• 5° rotation with 25% cropping: Fig. 21(c) was rotated counterclockwise by 5° and then 25% of image was cropped. The extracted watermark is shown in Fig. 21(d).

•旋轉 5°並裁剪 25%：將圖 21（c）逆時針旋轉 5°，然後裁剪 25%的圖像。 所提取的水印如圖 21（d）所示。

• 5° rotation, 25% cropping, and histogram equalization: Histogram equalization was performed on the watermarked image above (after 5° rotation and 25% cropping). The extracted watermark is shown in Fig. 22(b).

•5°旋轉，25%裁切和直方圖均衡：對上方的水印圖像進行直方圖均衡（5°旋轉和 25%裁切後）。 提取的水印如圖 22（b）所示。

• 5° rotation, 25% cropping, and sharpening: The watermarked image (Fig. 22(c)) was rotated counterclockwise by 5°. Then, the 25% of rotated image was cropped and was sharpened subsequently. The extracted watermark is shown in Fig. 22(d).

•旋轉 5°，裁剪 25%，並變清晰：將帶水印的圖像（圖 22（c））逆時針旋轉 5°。 然後，裁剪 25%的旋轉圖像，然後將其銳化。 提取的水印如圖 22（d）所示。

A BER comparison for various combined attacks is shown in Fig. 23. The proposed method has better BER values in all cases, and is approximately improved by 16%.

圖 23 顯示了各種組合攻擊的 BER 比較。所提出的方法在所有情況下都具有更好的 BER 值，大約可提高 16%。

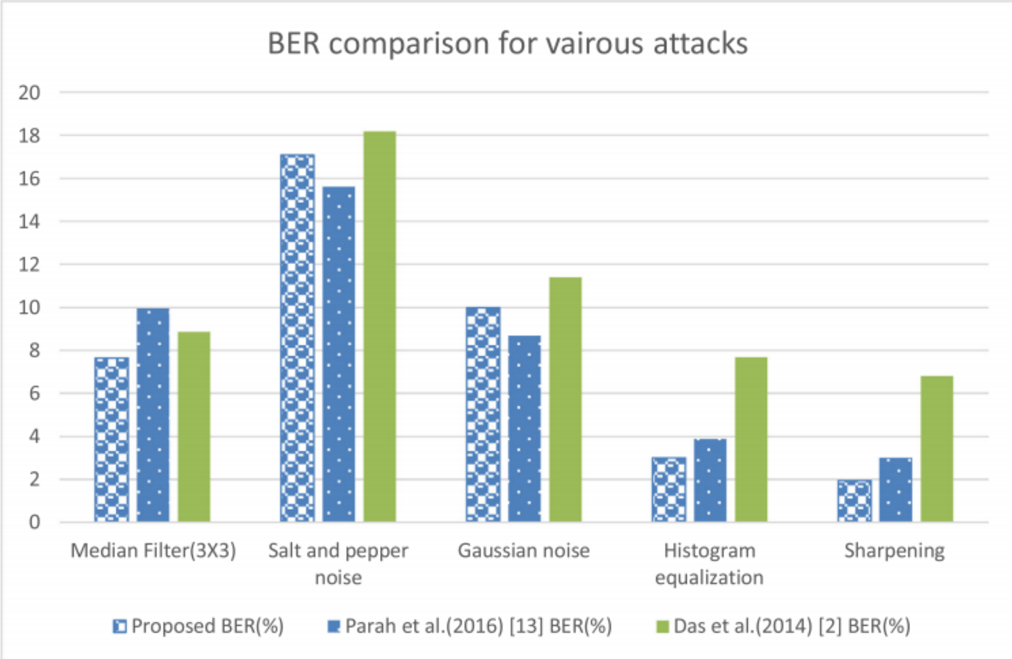


Fig. 20. BER comparison for various attacks.

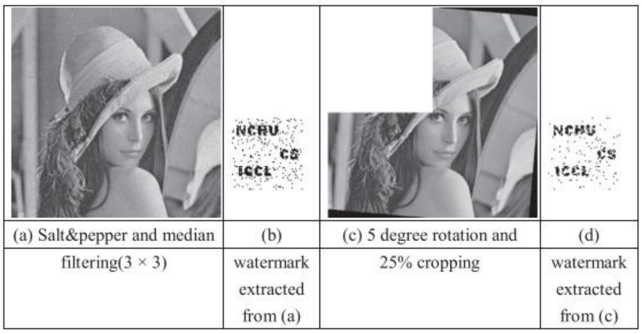


Fig. 21. Two examples of the proposed method with combined attacks: (a) watermarked images with salt&pepper noise and median filtering(3 × 3), (b) BER of extracted watermark is 7.95%, (c) watermarked image with 5° rotation and 25% cropping, and (d) BER of extracted watermark is 4.68%.

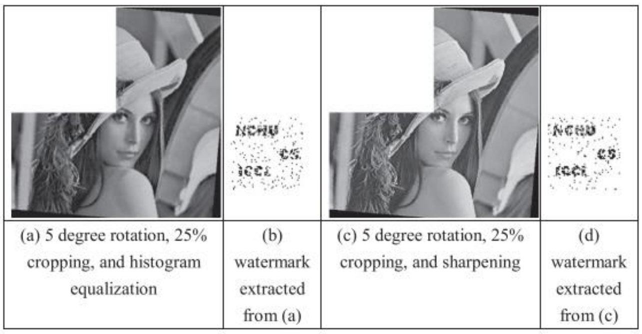


Fig. 22. Two examples of the proposed method with three combined attacks: (a) watermarked image with 5° rotation, 25% cropping, and histogram equalization, (b) BER of extracted watermark is 6.76%, (c) watermarked image with 5° rotation, 25% cropping, and sharpening, and (d) BER of extracted watermark is 6.25%.

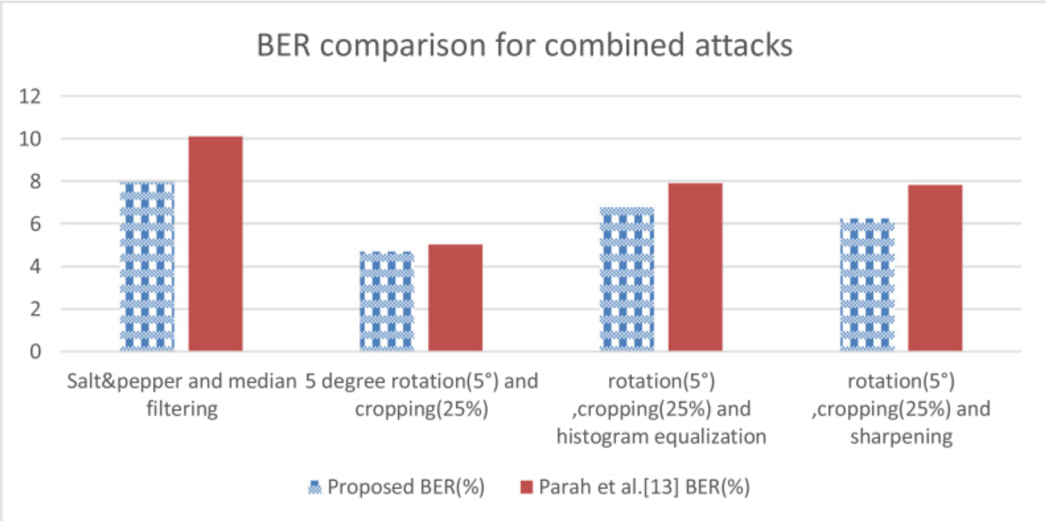


Fig. 23. BER comparison with various combined attacks.

5. Conclusion

Herein, a novel watermarking method based on the inter-block DCT coefficient correlation has been proposed. The threshold value changes periodically to initiate security for preventing a variety of attacks and represents inherent limitation in the proposed algorithms of our study. The proposed method considers coefficient correlation and we apply minor changes in each 8 × 8 DCT block. The averaged BER of cropping and rotating attacks obtained using the proposed method is lower than that proposed by Parah et al., with an improvement ratio of over 23%. Furthermore, PSNR obtained herein remains higher than that obtained by Parah et al. The perceptual image quality demonstrates that the proposed watermarking method outperforms the previous methods. We demonstrated good robustness against single and combined attacks, such as cropping, rotation, and median filtering. The averaged BER of the extracted watermark after combined attacks remains lower than that obtained by Parah et al., with an approximate improvement of 16%. In comparison with the previous methods, the proposed method is more effective for the copyright protection of digital images.

在此，提出了一種新的基於塊間 DCT 係數相關性的水印方法。閾值定期更改以啟動安全性以防止各種攻擊，並且代表了我們研究中提出的算法的固有局限性。所提出的方法考慮了係數相關性，我們在每個 8×8 DCT 塊中應用較小的變化。使用該方法獲得的耕作和輪作攻擊的平均 BER 低於 Parah 等人提出的 BER，改進率超過 23％。此外，本文獲得的 PSNR 仍然高於 Parah 等人獲得的 PSNR。感知圖像質量表明，所提出的水印方法優於先前的方法。我們展示了針對單一和組合攻擊（如裁剪，輪播和中值過濾）的良好魯棒性。聯合攻擊後提取的水印的平均 BER 仍然低於 Parah 等人獲得的 BER，大約提高了 16％。與以前的方法相比，該方法對數字圖像的版權保護更為有效。

Appendix A

Das et al. Method and its DCT block matrix operation is shown in Fig. A1:

Das 等。 方法及其 DCT 塊矩陣運算如圖 A1 所示：

Input: cover image I, watermark WM

Output: watermarked image Iw

DC: the top-left coefficient of a block

Bx,y: An 8 × 8 DCT block, where, x is index of row number and y is index of column number of blocks

Z: scaling variable

44 H.-J. Ko, C.-T. Huang and G. Horng et al. / Information Sciences 517 (2020) 128–147

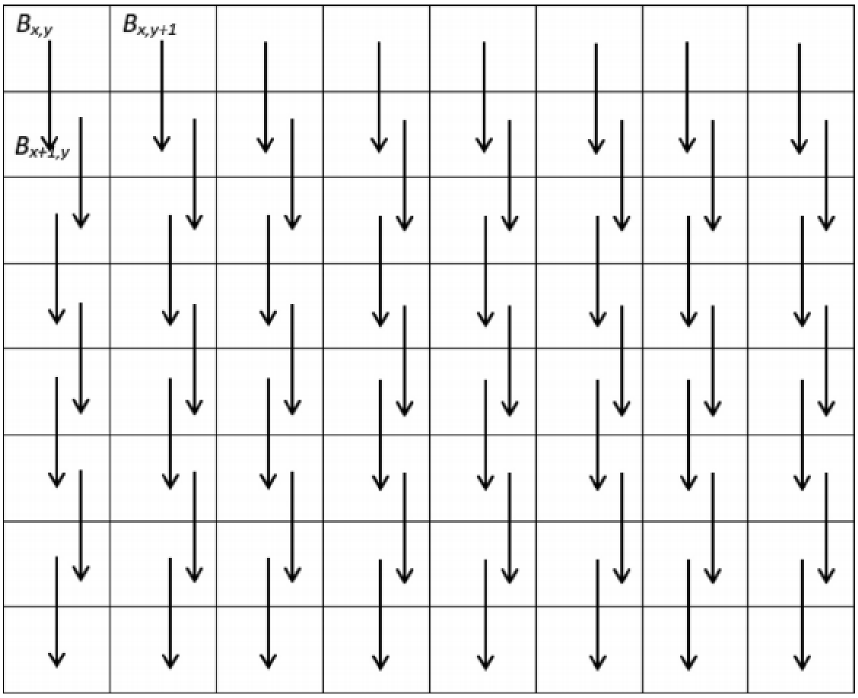


Fig. A1. DCT block matrix operation (Das et al. [2]).

Th: threshold.
K: variable which is less than Th.

$B_{x,y}(i, j)$:	A DCT coefficient inside a $B_{x,y}$ DCT block
Step 1.	Each pixel value of *I* is subtracted by 128
Step 2.	*I* is transformed via DCT block by block (each block size is 8 × 8)
Step 3.	Compute median of first 11 zig-zag ordered AC coefficients as Med
Step 4.	Compute modification parameter *P* (DC is (0,0) of DCT block; *Z* is set to 2) $P = =Z \times ((DC - Med)/DC)$
Step 5.	WM is permuted by with a pseudorandom bits named key

Step 6.	Select a coefficient from (0,1), (2,0), (0,2), and (1,2) or (1,0), (1,1), (0,3), and (2,1); the selected coefficient is $B_{x,y}(i, j)$
	Th is set to 80; *K* is set to 12
	embed WM bit 1:
	If $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) > Th - K$ *Then*
	While $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) > Th - K$
	$B_{x,y}(i, j) = B_{x,y}(i, j) - P$
	End While
	Else If $((B_{x,y}(i, j) - B_{x+1,y}(i, j)) < K)$ && $((B_{x,y}(i, j) - B_{x+1,y}(i, j)) > -Th/2)$
	Then
	While $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) < K$
	$B_{x,y}(i, j) = B_{x,y}(i, j) + P$
	End While
	Else If $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) < -Th/2$
	Then
	While $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) > -Th - K$
	$B_{x,y}(i, j) = B_{x,y}(i, j) - P$
	End While
	embed WM bit 0:
	If $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) > Th/2$
	Then
	While $-((B_{x,y}(i, j) - B_{x+1,y}(i, j)) > Th + K)$ $B_{x,y}(i, j) = B_{x,y}(i, j) + P$
	End While
	Else If $((B_{x,y}(i, j) - B_{x+1,y}(i, j)) > -K)$ && $((B_{x,y}(i, j) - B_{x+1,y}(i, j)) < Th/2)$
	Then
	While $-((B_{x,y}(i, j) - B_{x+1,y}(i, j)) < -K)$
	$B_{x,y}(i, j) = B_{x,y}(i, j) - P$

(continued on next page)

	End While *Else If* $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) < -Th + K$ *Then* *While* $-((B_{x,y}(i, j) - B_{x+1,y}(i, j)) > -Th + K)$ $B_{x,y}(i, j) = B_{x,y}(i, j) + P$ *End While*
Step 7.	Apply Inverse DCT on each block as I_w
Step 8.	Add 128 to each pixel of I_W

LR:

$$D = B_{x,y}(i, j) - B_{x,y+1}(i, j)$$

RD and LD:

$$D = B_{x,y}(i, j) - B_{x+1,y}(i, j)$$

RL:

$$D = B_{x,y}(i, j) - B_{x,y-1}(i, j)$$

Appendix B

Parah et al. Method:

Parah et al. increases the capacity of a watermark using the all blocks. Their experimental results showed that their method has better robustness than Das et al. The method used by Parah et al. is described as follows, and its DCT block matrix operation is shown in Fig. B1.

Parah 等。 使用所有塊增加水印的容量。 他們的實驗結果表明，他們的方法具有比 Das 等人更好的魯棒性。 Parah 等人使用的方法。 如下所述，其 DCT 塊矩陣操作如圖 B1 所示。

Input: cover image I, watermark WM

Output: watermarked image Iw

T: threshold

E: embedding factor

V: scaling variable

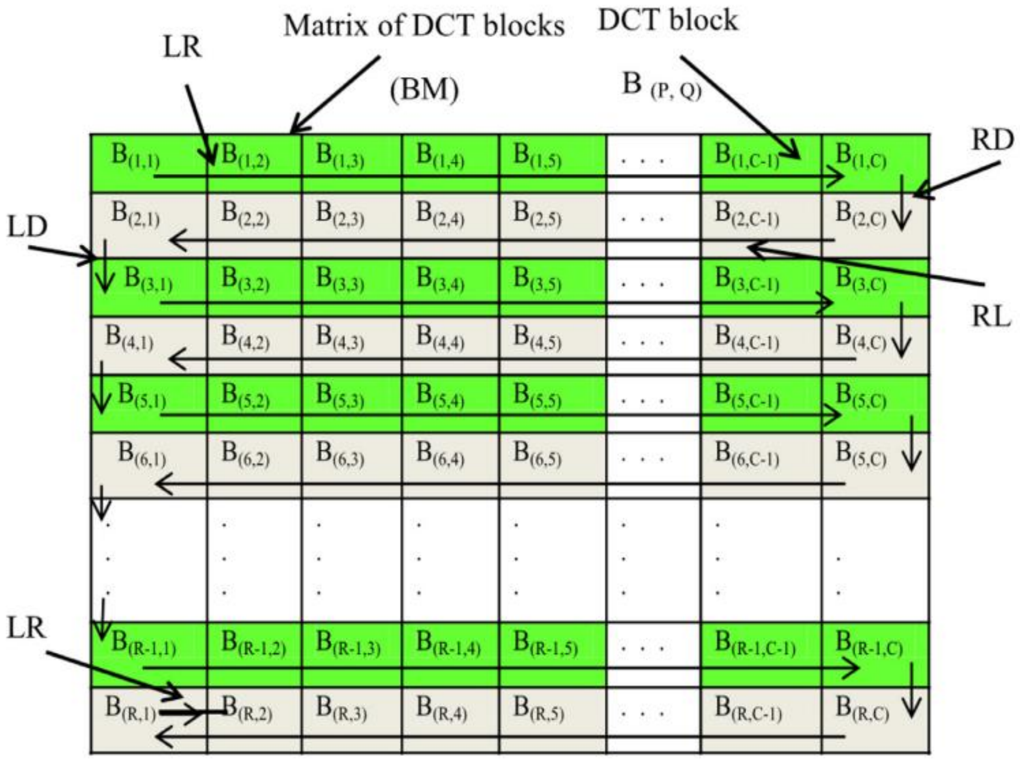


Fig. B1. DCT block matrix operation (Parah et al. [13]).

Step 1.	Each pixel value of I is subtracted by 128
Step 2.	I is transformed via DCT block by block (each block is 8×8)
Step 3.	Compute median of the first 9 zig-zag ordered AC coefficients as Med
Step 4.	Compute modification parameter m (DC is (0,0) of DCT block; V is set to 0.5) $m = = V \times ((DC - Med)/DC)$
Step 5.	WM is permuted by random bits named key
Step 6.	Select a coefficient from the middle frequency band; the selected coefficient is $B_{x,y}(i, j)$; compute D

Step 7.	T is set to 80; E is set to 12
	Embed WM bit 1:
	If $D > T - E$ *Then*
	While $(B_{x,y}(i, j) - B_{x+1,y}(i, j)) < T - E$
	$B_{x,y}(i, j) = B_{x,y}(i, j) - m$
	End While
	Else If $(D <= E)$ && $(D > -T/2)$
	Then
	While $D > E$
	$B_{x,y}(i, j) = B_{x,y}(i, j) + m$
	End While
	Else If $D <= -Th/2$
	Then
	While $D > -T - E$
	$B_{x,y}(i, j) = B_{x,y}(i, j) - m$
	End While
	embed WM bit 0:
	If $D >= T/2$
	Then
	While $\sim(D > T + +E)$
	$B_{x,y}(i, j) = B_{x,y}(i, j) + m$
	End While
	Else If $(D >= -E)$ && $(D < T/2)$
	Then
	While $\sim(D < -E)$
	$B_{x,y(}i, j) = B_{x,y}(i, j) - m$
	End While
	Else If $D < -T + +E$
	Then
	While $\sim(D > -T + +E)$
	$B_{x,y}(i, j) = B_{x,y}(i, j) + m$
	End While

Step 8.	Apply Inverse DCT on each block as I_w
Step 9.	Add 128 to each pixel of I_W