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The performance of Circular and Adaptive Embedding Methods in Imperceptible Data Hiding using DWT

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Abstract

This work investigates three watermark embedding schemes in the discrete wavelet transform (DWT) domain: circular, adaptive circular, and texture-adaptive circular embedding. Each method embeds a binary watermark into the LL subband of a 1-level DWT using concentric rings to define the spatial pattern. Circular embedding applies uniform strength across rings, adaptive circular embedding adjusts inner-ring strength to account for human visual perception, and texture-adaptive circular embedding further modulates strength based on local image variance. The paper presents a fair and normalized comparison of imperceptibility among the three methods using PSNR and SSIM metrics.

Keywords: Circular Embedding; Image Quality; Perceptual Maps; Digital Image Processing.

1 | Introduction

Digital image watermarking aims to hide information in an image while keeping the watermark imperceptible. In other words, the watermarked image should look virtually identical to the original so that the watermark is invisible to a casual viewer. Standard objective metrics for image quality, such as peak signal-to-noise ratio (PSNR) and structural similarity (SSIM), are routinely used to quantify this invisibility. Higher PSNR or SSIM values generally indicate that the watermark has a minimal impact on visual quality. In fact, an effective watermarking system achieves high PSNR/SSIM at a given payload, meaning no perceptible difference between host and watermarked image[1]. Achieving imperceptibility typically involves modeling the human visual system (HVS). Perceptual models like just-noticeable-difference (JND) thresholds and visual masking are used to adapt the watermark strength according to image content. For example, the HVS is less sensitive to changes in very bright regions and in highly textured or busy areas [2].

Watermarking methods vary in how they distribute the watermark and adapt to content. A common approach is to work in a transform domain. For instance, wavelet-based (DWT) methods embed the watermark across subbands to spread energy and improve imperceptibility.

Other works use circular or ring-based embedding: the transform coefficients are partitioned into concentric rings or frequency bands, and the watermark is inserted in these rings. Such ring-based schemes have been shown to outperform traditional block embeddings in some cases [3]. However, prior studies have generally



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tested these methods under different conditions. Few papers have directly compared circular embedding, adaptive circular embedding, and texture-adaptive circular embedding using the same payload and embedding parameters.

In this paper we fill that gap by evaluating the visual quality of three circular watermarking strategies under identical conditions. We implement (1) simple circular embedding, (2) adaptive circular embedding, and (3) texture-adaptive circular embedding with the same payload, embedding strength, and normalization. Each method is applied to a standard set of ten grayscale test images. We then measure PSNR and SSIM between the original and watermarked images to assess imperceptibility. The focus is strictly on visual quality, not on robustness; indeed, increasing robustness typically requires stronger (more visible) embedding.

The presented paper working to evaluate the aforementioned circular strategies by two subjective measurements, PSNR and SSIM.

2 | Literature Studies

Digital image watermarking has been used in different literature studies to provide ownership protection, checking data integrity or recovering altered data [4, 5].

Existing watermarking methods can be categorized based on dealing with image pixels into spatial domain and transform domain approaches. Spatial domain methods, such as simple least-significant-bit (LSB) modifications, uses the image pixels directly and alter them according to the watermark. However, they are highly vulnerable to alterations, and the resultant watermarked image is fragile to attacks (for instance, resetting LSB from all pixels). Consequently, transform domain embedding, which allows the watermark to be embedded in frequency domain as wavelet components of the image, providing a better balance between imperceptibility and robustness in watermark recovery.

Among the transform domain methods, the Discrete Wavelet Transform (DWT) has been introduced as one of the most widely watermark preprocessing tools. The DWT provides a multi-resolution decomposition of the image, allowing it to localize both spatial and frequency information of the image. Compared to other transforms such as the Discrete Cosine Transform (DCT) Discrete Fourier Transform (DFT) or Singular Value Decomposition (SVD), DWT-based watermarking is particularly advantageous for imperceptible embedding because it can selectively target image areas based on their frequency and spatial characteristics. This makes it possible to embed watermarks in regions where alteration are less perceptible to the human visual system (HVS) [6, 7].

In recent researches, researchers have gradually focused on adaptive embedding techniques, which adjust the watermark according to the sensitivity of human eye to different image structures. One major direction is texture-aware embedding, which takes advantage of the fact that the human visual system is less sensitive to changes in highly textured or complex regions of an image. For example, Huang et al. [8] proposed a texture-aware local watermarking scheme guided by the structural similarity index (SSIM). In their approach, more watermark bits are placed in high-texture regions, resulting in minimal perceptible distortion while maintaining high image quality. Similarly, Taha et al. [9] utilized an integer form of LWT, which is lifting wavelet transform (LWT) to generate a texture mask, identifying areas with higher embedding capacity, the same LWT is used to embed the watermark in different intensities depending on the texture mask, edges mask and luminance mask. These studies determined that adapting the watermark to local image characteristics can significantly improve perceptual quality.

Another approach to watermarking research is circular embedding or ring embedding, which embeds the watermark in concentric rings emanating from the center of the host image. Circular embedding has been investigated in the past mostly from the point of view of robustness against geometric operations such as rotation; however, it is important from the point of view of imperceptibility. The watermark is embedded in rings instead of blocks, which helps to distribute the watermark more evenly across the image and thereby minimises visible watermark artefacts in sensitive areas. Example of that is the work of Chiu and Tsai [10]

proposed a notable DFT-domain watermarking method where coefficient-value peaks are embedded symmetrically in circular patterns within a middle-frequency ring band. Although originally designed to maintain synchronization and detection after geometric attacks, the use of circularly placed peaks in a frequency band, and reflects attention to visual imperceptibility. Their strategy of embedding in the red and blue channels while preserving symmetry ensures better quality, and their experimental results confirm that the PSNR of resultant images remained acceptable for visual quality. Moreover, their system's design mirrors the structural layout found in modern circular embedding strategies, although focused more on synchronization than visual modeling.

To place watermark bits along concentric regions by considering the HVS, Wang et al. [11] proposed a blind circular embedding scheme based on empirical mode decomposition. While these methods are in the name of more robust results, the concept of ring-based, uniform distribution is also very relevant to perceptual quality, because if these methods used block-based embedding there could be localized distortion.

These methods and others that take into account what is known as Just Noticeable Difference (JND), that's where most people are able to see the difference. That is, it estimates the largest distortion that a picture can undergo without changes being perceptible [12]. The models simulate different aspects of the HVS including texture masking, luminance masking, contrast sensitivity and other visual phenomena. The embedding of the JND thresholds into the embedding process can guarantee that the modifications do not exceed the perceptual limits. Most of the adaptive and texture-aware watermarking research incorporates these ideas, varying the embedding strength based on the local texture and global visual sensitivity of the image.

In spite of these developments, there is no systematic, quantitative comparison in the literature of circular, adaptive circular and texture-adaptive circular embedding, focusing on image quality. Most of the previously published works are concerned with robustness against compression, noise, cropping, etc., and there is very little evidence of the performance of the adaptive and/or texture-based methods over multiple images containing different textures and structures under controlled and identical conditions.

This paper addresses this deficit by implementing and evaluating three circular embedding schemes-circular, adaptive circular, and texture-adaptive circular-which are focused purely on visual quality and fairness of comparison. The proposed methods are applied to a set of ten grayscale images by using the same watermark payload, base embedding strength, and normalization approach in order for the results of the comparison with one another to be related to differences in embedding strategy and not to any extrinsic factors. By systematic measurement of PSNR and SSIM values, it is shown how adapting the watermark strength according to ring position and local texture can preserve image fidelity while remaining imperceptible. It follows that this work provides new insights into how embedding schemes interact with image properties to affect perceptual quality, which is a subject that has been largely overlooked in previous studies.

3 | Methodologies

In this paper, all watermarking methods were implemented in the discrete wavelet transform (DWT) domain, using the Haar wavelet for its simplicity and efficient spatial-frequency localization. The DWT decomposes the image into four sub bands: LL, LH, HL, and HH, as shown in Figure 1. Among these, the LL sub band contains the largest portion of the image's energy and represents the coarse approximation of the original image. Because of its stability and energy concentration, it has become a preferred host for watermark embedding in many transform-based watermarking systems [13]. However, embedding in LL also presents a fundamental trade-off: it enhances robustness because modifications in this sub band are less affected by compression and filtering, but it can reduce imperceptibility since changes here are more likely to alter the visual content.

To maintain a fair and consistent experimental environment, all watermarking schemes in this work embed a binary watermark of size 64×64 into the LL subband of a 1-level 2D DWT applied to a 512×512 grayscale host image. This configuration was selected to achieve a practical balance between embedding capacity, visual

transparency, and computational simplicity. After embedding, the inverse DWT (IDWT) reconstructs the spatial-domain watermarked image, allowing direct visual comparison and quantitative evaluation using standard image quality metrics (PSNR and SSIM).

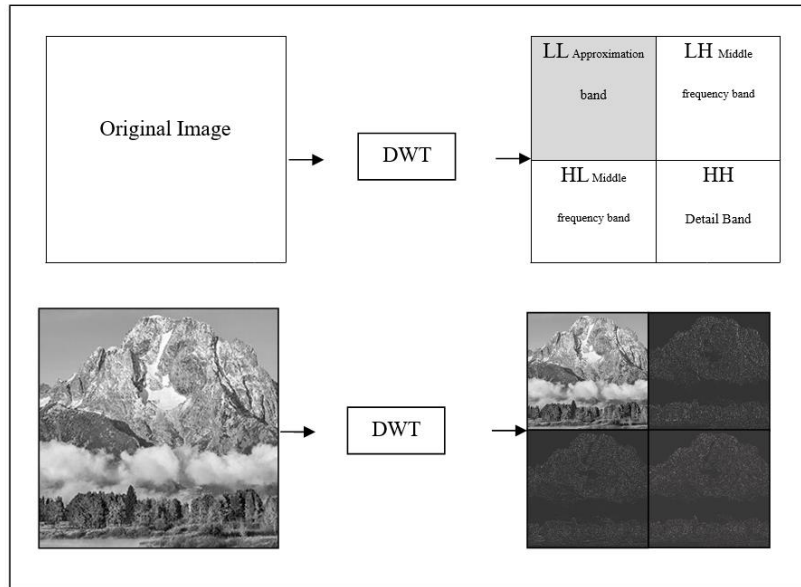


Figure 1. One-level 2D DWT decomposition of an image into LL (low-low) and HL, LH, HH sub bands.

Following this methodological setup, three circular-based strategies are examined: the basic circular embedding, adaptive circular embedding, and texture-adaptive circular embedding. Each of these modifies the watermark distribution or embedding strength according to different perceptual principles, which are discussed in detail in the subsequent sections.

3.1 | Uniform Circular embedding

Rather than dividing the LL sub band into square blocks, the sub band was divided to circular rings (called annuli) centered on the center of the image. These rings are assigned to each pixel depending on its distance from the centre. Each ring contains one bit of the information to be hidden and all the pixels are adjusted in the same manner, either increased or decreased in brightness by a small amount depending on the bit value.

This circular method has an advantage: if the image is rotated around its center, each pixel stays within the same ring, so the hidden data remains unchanged. This gives the method good resistance to rotation. Studies have shown that using circular areas instead of square blocks usually leads to higher image quality scores (PSNR), because the changes are spread more evenly across the image.

However, the downside is that the very center of the image can be noticeably affected, since even the smallest inner ring is modified just like the outer ones. As a result, the structural similarity (SSIM) near the center may drop. In addition, the edges between rings can sometimes cause faint circular artifacts.

3.2 | Adaptive Circular Embedding (Radial Weighting)

To address the limitation of uniform circular embedding, where all rings are modified with equal strength, causing visible artifacts near the center, the adaptive circular embedding introduces a perceptually guided modulation of watermark strength based on radius. The method begins by dividing the low-frequency sub-band (LL) into a series of concentric rings from center to outward. Each ring represents a zone in which one bit of the watermark will be embedded. Instead of applying a constant modification strength to all rings, the embedding amplitude is gradually increased from the center toward the periphery. This design aligns with the characteristics of the human visual system, which is more sensitive to changes in the central region and less sensitive in remote from center areas.

In embedding, every ring is given a strength that is proportional to how far it is from the centre, so that the less sensitive the central part of the photo, the weaker the perturbation; the further from the centre, the stronger the perturbation. The modification is applied to all the rings in the same manner based on the bit being embedded giving coherent and consistent encoding. A mild blending or smoothing algorithm can be applied to edges between neighbouring rings to reduce the appearance of faint circular edges, which may occur. This slow adaptation function is radius-dependent, which creates a more perceptually pleasing watermark, resulting in better structural similarity (SSIM) while retaining high peak signal-to-noise ratio (PSNR) and robustness as the embedding strength is stronger in the outer areas. While the adaptive circular approach is more resilient and invisible in practice, minor artefacts can be seen in flat outer parts due to the lack of local texture to mask changes.

3.3 | Texture-Aware Adaptive Circular Embedding

The texture aware method is a development of the previous method, where the embedding strength is refined based on local characteristics of the host image. It considers the texture level of each ring, and assigns the initial embedding severity based on that level. The rings with higher texture are expected to have tolerance to more embedding strength, while areas with low texture have subtle embedding to avoid visual distortion.

The final embedding strength for each ring is obtained by scaling the radial strength according to its texture level, thereby reducing energy in smooth areas and retaining nearly full strength in highly textured ones. This dual adaptation ensures that watermark energy is concentrated in perceptually tolerant regions—those that are either peripheral or rich in texture—while minimally altering smooth or flat regions. The result is a watermark that remains robust yet visually indistinguishable from the original image. Texture-aware embedding thus preserves flat structures almost exactly, leading to the highest structural similarity values among all tested schemes, while maintaining strong robustness through effective use of textured regions. Although the additional texture analysis introduces computational overhead, it provides the most perceptually balanced and visually consistent watermarking performance, mitigating both central distortions and circular artifacts observed in earlier methods.

Figure 2 shows the embedding for each, here, the embedding strength was intentionally exaggerated to 1.05 to demonstrate the difference the watermark impact. However, the values were settled to accepted ones in results section.



Figure 2. Circular Embedding: from top left: Original, regular circular embedding, Adaptive Circular Embedding, Texture-Aware Adaptive Circular Embedding.

4 | Results and Discussion

This section shows the obtained results while applying different embedding methods, the performance was measured using Structural Similarity Index (SSIM) and Peak Signal to Noise Ratio (PSNR)

4.1 | Embedding Strategies

be placed To evaluate the visual quality and fairness of the embedding we implemented and compared three watermark embedding methods in the DWT domain: circular embedding, adaptive circular embedding, and texture-adaptive circular embedding. To achieve the embedding in fair way between different methods, multiple factors need to be controlled. In our study, all three methods: circular, adaptive circular, and texture-adaptive circular embedding; used the same watermark payload of 128 bits. This guarantees that each method carries the same amount of information, eliminating bias caused by different watermark sizes.

Furthermore, the embedding strength was initially set to the same base value for all methods. For adaptive methods, the strength was locally adjusted based on the distance from the image center or the local texture; however, the overall energy of embedding remained comparable across methods.

In addition, the circular embedding schemes normalize the modification by the size of each ring, ensuring that larger rings do not dominate the effect of the watermark. Finally, the watermark bits were include an approximately equal number of zeros and ones, preventing skewed embedding patterns. By carefully controlling these factors, we achieved a fair and scientifically meaningful comparison, allowing differences in results to reflect the design of each embedding method rather than external factors.

4.2 | Evaluation Metrics:

Ten standard images were chosen for the evaluation of embedding methods. Thumbnails of tested images are shown in Figure 3.



Figure 3. Thumbnail of tested images labeled as I1-I10 Left to right top to bottom.

The evaluation of the imperceptibility of the watermark using two metrics, PSNR (Peak Signal-to-Noise Ratio): Measures the similarity between the original and watermarked images. Higher PSNR indicates less visible change and SSIM (Structural Similarity Index) [14]: Measures the structural similarity between images. SSIM values closer to 1 indicate higher visual similarity.

The PSNR and SSIM values in Tables 1 and 2 demonstrate the visual quality of the watermarked images across the ten test images.

Table 1. PSNR For tested Images.

Image	Circular	Adaptive Circular	Texture Adaptive Circular
I1	44.63	47.42	50.64
I2	41.85	42.69	49.06
I3	45.80	48.89	50.98
I4	43.60	46.89	49.85
I5	42.10	43.64	49.22
I6	44.96	48.42	50.22
I7	41.09	43.10	48.67
I8	44.12	47.56	49.59
I9	43.03	43.97	49.56
I10	38.08	40.01	44.81

Table 2. SSIM For tested Images.

Image	Circular	Adaptive Circular	Texture Adaptive Circular
I1	0.9905	0.9948	0.9976
I2	0.9812	0.9843	0.9970
I3	0.9893	0.9952	0.9976
I4	0.9865	0.9940	0.9976
I5	0.9856	0.9896	0.9978
I6	0.9904	0.9959	0.9977
I7	0.9765	0.9855	0.9965
I8	0.9935	0.9964	0.9976
I9	0.9844	0.9862	0.9971
I10	0.9520	0.9686	0.9901

4.3 | Discussion

From obtained results, one can find the impact of watermark distribution strategy on the perceptual quality of the watermarked image. The three tested methods, namely: Circular, adaptive circular, and texture adaptive circular, all use the same watermark, embedding strength and embedding payload but the results were different.

The circular embedding methods shows the less subjective quality measurements (PSNR and SSIM) values. This is because it applies uniform changes to all image areas (represented by low frequency band coefficients) However, the circular pattern provides acceptable imperceptibility due to its symmetric design as the average values of PSNR 42.926 (regardless the robustness) and SSIM 0.98.

The adaptive circular has a subtle but effective improvement by assigning different embedding strengths as the ring has more distance from the image center. The methods assign less embedding strength in the center of the image where the eye is more sensitive. Then it's gradually increases the strength toward the periphery, where visual sensitivity decreases. The average of PSNR is 45.259 and SSIM is 0.98905 using this method.

In the third method, the texture-adaptive circular embedding further improved the adaptive circular by introducing local texture analysis into the embedding process. Instead of relying solely on distance from the image center, this method adjusts the embedding strength according to both radial position and local texture statistics (mean and standard deviation). High-texture regions, where the eye is naturally less sensitive to small intensity changes, receive stronger embedding, while smooth or uniform regions where any distortion would

be easily noticed, receive weaker embedding. This dual adaptation, combining spatial and textural cues, results in the highest PSNR and SSIM values among all tested methods, where the average PSNR was 49.26 and SSIM was 0.99666.

Although the PSNR is a quotative value and not considering the perceptual quality, but it still having different values in the three tested methods. Circular: All rings are treated in the same way. Therefore even pixels in smooth and bright central regions, with high LL values, would get the same proportional change. This results in increase in pixel intensity differences and increase in MSE leads to decrease in PSNR. Adaptive circular embedding is where the strength is smaller in the center and larger in the periphery. The number of central pixels usually is high and these pixels have high energy, so when the distortion of central pixels is reduced, the average MSE will be reduced, which results in the increase of PSNR. In texture adaptive circular embedding, the smooth regions are modified less, and the more complex (textured) regions are stronger embedded. Because high-texture areas have high local variance, small modifications there do not significantly raise global MSE and hence, higher PSNR.

Overall, the results demonstrate that perceptual adaptation whether spatial (radial) or local (texture-based) — plays a decisive role in improving image quality. The comparison among the three circular strategies provides clear evidence that incorporating models inspired by the human visual system (HVS) leads to higher imperceptibility. The consistent use of identical embedding parameters across all methods ensures that the observed differences are solely due to the embedding design rather than uncontrolled experimental factors.

5 | Conclusion

This paper presented a fair and normalized comparison among three DWT-based watermarking methods: circular, adaptive circular, and texture-adaptive circular embedding. The results showed that the adaptive approaches significantly enhance imperceptibility compared to the basic circular method. Among them, the texture-adaptive circular embedding achieved the best subjective results of PSNR equal 49.26 to and SSIM equal to 0.99666 for embedding strength 0.05 of an embedded watermark of the size 64×64. Proving to be the most effective in preserving visual quality while keeping the watermark invisible. Future work may extend this approach to color images and employ more advanced perceptual models to further refine embedding adaptation in accordance with human visual sensitivity.

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Conflicts of Interest

The authors declare that there is no conflict of interest in the research.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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