



A Robust Hybrid Image Watermarking Scheme Based on IWT-DCT-SVD using Entropy and Edge Entropy

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Abstract

The rapid expansion of digital multimedia distribution has increased the demand for dependable copyright protection and content authentication. Digital image watermarking has emerged as a principal solution, yet the fundamental challenge remains in balancing imperceptibility and robustness against various signal processing and geometric attacks. This paper proposes a novel hybrid watermarking scheme that combines the Integer Wavelet Transform (IWT), the Discrete Cosine Transform (DCT), and Singular Value Decomposition (SVD), while entropy and edge entropy decide where the watermark is embedded. The use of IWT overcomes the floating-point precision loss inherent in conventional Discrete Wavelet Transform (DWT), ensuring perfect reconstruction and higher accuracy in watermark extraction. DCT is employed to leverage energy compaction in mid frequency bands, while SVD provides exceptional stability against geometric distortions due to the inherent invariance of singular values. The critical innovation lies in the integration of entropy and edge entropy metrics to dynamically identify highly textured image blocks with maximum natural masking capacity. Unlike conventional HVS or variance-based methods that often mischaracterize directional edges, the proposed dual-entropy model precisely quantifies both luminance obliviousness and structural sensitivity, enabling the embedding of stronger watermarks without compromising perceptual quality. Extensive experiments on eight standard 512×512 benchmark images demonstrate consistently high imperceptibility, with an arithmetic average PSNR of 40.46 dB, SSIM of 0.9965, and FSIM of 0.9995. Robustness evaluations under fourteen categories of signal processing and geometric attacks yield Normalized Correlation (NC) values predominantly above 0.99, outperforming four recent state-of-the-art methods in eleven of twenty attack scenarios. The identified limitations include reduced robustness against large-angle rotation attacks, an inherent SVD challenge. The proposed framework demonstrates significant potential for secure, imperceptible digital image watermarking.

Keywords: entropy; edge entropy; hybrid image watermarking; imperceptibility; robustness

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1. Introduction

The digital revolution has transformed the creation, storage, and dissemination of multimedia content. Digital images, being one of the most prevalent forms of information, are highly vulnerable to unauthorized copying, manipulation, and redistribution [1]. To address this ubiquitous challenge, robust mechanisms for copyright enforcement, content authentication, and tamper detection are imperative. Consequently, digital

image watermarking has emerged as a highly effective technique for seamlessly integrating ownership data into digital media, ensuring its resilience against standard signal processing manipulations. [2].

A digital watermarking system must fundamentally satisfy two often conflicting requirements: imperceptibility and robustness [3]. Imperceptibility is the extent to which a watermark can be embedded without introducing visible artifacts, whereas

robustness is the capacity of the watermark to withstand intentional or unintentional attacks. In this study, the payload is fixed at a 256×256 binary logo so that the evaluation concentrates on optimizing the imperceptibility-robustness trade-off under compression, filtering, noise addition, and geometric transformations [4].

Early spatial-domain techniques such as Least Significant Bit (LSB) substitution are simple and provide high capacity, but even mild attacks can destroy the embedded data [5]. To improve robustness, transform-domain methods were developed. Discrete Cosine Transform (DCT) watermarking, motivated by the JPEG standard, inserts the watermark into mid-frequency coefficients and thereby achieves a favorable compromise between imperceptibility and robustness [6]. Discrete Wavelet Transform (DWT) methods provide multi-resolution analysis and joint spatial-frequency localization, which permits embedding in selected sub-bands [7]. However, DWT introduces floating-point computation errors due to rounding during the inverse transformation, making it unsuitable for applications requiring lossless reconstruction, such as medical imaging and legal documentation [8].

Recent hybrid approaches combine IWT with DCT and Singular Value Decomposition (SVD) to exploit their complementary strengths: IWT ensures precision, DCT provides robustness against compression, and SVD offers stability against geometric attacks due to the invariance of singular values [9]. Hybrid approaches that combine IWT with DCT and Singular Value Decomposition (SVD) leverage their complementary properties: IWT provides integer-precision decomposition, DCT offers energy compaction and compression resilience, and SVD ensures stability against geometric distortions due to the invariance of singular values. A fixed scaling factor often leads to either visible distortion (if too high) or insufficient robustness (if too low).

Entropy and edge entropy describe how sensitive the human eye is to changes in luminance, texture, and contrast, allowing adaptive watermark embedding stronger in textured or bright regions, weaker in smooth or dark areas [10]. This paper therefore proposes a robust hybrid scheme that combines IWT, DCT, and SVD with an adaptive HVS model that computes a scaling factor for each block. The scheme works in the YCbCr color space and embeds the watermark in the luminance (Y) channel, since this channel carries most of the structural information and corresponds to HVS sensitivity.

The main contributions of this work include a novel hybrid IWT-DCT-SVD framework with integer precision that effectively eliminates floating-point errors. To enhance performance, an adaptive Human Visual System (HVS) model is introduced to compute block-specific scaling factors based on local luminance and texture masking. The proposed method maximizes both robustness and imperceptibility by embedding the

watermark directly into the Y channel of the YCbCr color space. Additionally, the framework incorporates an adaptive IWT decomposition level (R-Level) selection mechanism tailored to the watermark's size. Finally, comprehensive experimental validation is presented, demonstrating that this approach achieves superior imperceptibility and robustness when compared to current state-of-the-art methods.

Digital image watermarking research has evolved substantially over the past two decades, progressing from single-domain spatial methods to sophisticated multi-transform hybrid frameworks. This section critically reviews the most relevant developments and identifies the specific gaps that motivate the proposed approach. Early methods focused on single-transform domains. DCT-based watermarking, inspired by JPEG compression, embeds watermarks in mid-frequency coefficients to balance imperceptibility and robustness [11-15]. However, pure DCT methods are vulnerable to geometric attacks. DWT-based techniques gained popularity due to their multi-resolution capability, allowing watermark insertion in specific sub-bands (LL for robustness, HH for imperceptibility) [16-18]. Nevertheless, DWT's floating-point computations introduce rounding errors.

The hybrid watermarking philosophy emerged to harness complementary strengths and mitigate individual weaknesses. A hybrid system typically combines two or more transforms, embeds watermarks in multiple domains, or integrates auxiliary technologies like encryption or metaheuristic optimization. The combination aims to leverage the geometric invariance of one transform and the frequency resilience of another. SVD has been widely used due to its geometric invariance. Naffouti [19] combined DWT-SVD, reporting a good balance between imperceptibility and robustness, but the method remains susceptible to DWT's floating-point inaccuracies. Kapoor et al. [20] and provided a comparative analysis of DWT-DCT-SVD variants but did not explore IWT, and some researchers use this hybrid schema for watermarking [21-26].

To address this, researchers began adopting IWT. For instance, Shubuh and Ernawan [27] proposed an IWT-DCT-SVD scheme with R-Level decomposition, achieving high SSIM (0.99943). Their method adapts decomposition level based on watermark size but does not employ an adaptive HVS model for scaling factor optimization. Similarly, Wahyudi et al. [28] extended the IWT-DCT-SVD approach to color images using a multi-block strategy, though with increased complexity.

Recent studies have incorporated computational intelligence for parameter optimization. Particle Swarm Optimization (PSO) [29] and Artificial Bee Colony (ABC) [30] algorithms have been used to find optimal scaling factors. However, these metaheuristic approaches are computationally expensive. In contrast, HVS-based models offer a computationally efficient alternative for adaptive embedding [31].

The comprehensive review above reveals three key limitations in the state of the art. First, DWT-based hybrid methods, despite their prevalence, suffer from irreducible floating-point reconstruction errors that compromise reliability in precision-critical applications. Second, existing IWT-based schemes, while addressing the precision issue, employ fixed or non-adaptive scaling factors that cannot optimize the imperceptibility-robustness balance across diverse image content. Third, HVS-guided adaptive schemes in the literature are predominantly applied within DWT frameworks, leaving the integration of HVS models with IWT-based hybrid methods largely unexplored. The proposed IWT-DCT-SVD scheme with entropy and edge entropy-based HVS adaptation directly addresses all three identified gaps, as summarized in Table 1.

Table 1. Summary of Related Watermarking Schemes

Authors	Method	Advantages	Limitations
Y. Dong, R. Yan, and C. Yin [32]	Adaptive watermarking based on chaotic mapping	Enhanced security via chaotic sequences, good robustness, key-dependent security	Imperceptibility may be lower without HVS, key management critical, likely weak to geometric attacks
Y. Dong et al. [33]	Hybrid domain color watermarking using hyperchaotic mapping	High security for color images, utilizes color channel correlation, hybrid transform benefits	High computational complexity, may lack perceptual adaptation, potential over-engineering
R. Dwivedi and V. K. Srivastava [34]	IWT-based color watermarking using Hessenberg Decomposition (HD) and SVD	Computationally efficient due to HD, reversible IWT, good robustness profile	No adaptive HVS model, likely weak to geometric attacks, color-focused complexity
Sundhararaj et al. [26]	DWT-DCT-SVD	Detailed comparative analysis of α and NC	Does not use IWT for integer precision
M. Sahir et al. [35]	Optimized DWT-HD-SVD color watermarking	Optimized embedding parameters, balanced robustness-imperceptibility trade-off	High computational cost from optimization, risk of over-fitting, no explicit HVS guidance
Proposed Scheme	IWT-DCT-SVD + Adaptive HVS	Integer precision, adaptive scaling, high PSNR & NC	Slightly higher computational cost due to HVS computation

The proposed watermarking scheme has two main phases: watermark embedding and watermark extraction. The overall architecture operates in the YCbCr color space, embedding the watermark exclusively in the luminance (Y) channel to leverage

HVS alignment. The following subsections present the mathematical foundations of each component and a detailed description of the embedding and extraction algorithms.

2. Methods

This section details the methodology of the proposed robust hybrid image watermarking framework, which brings together the Integer Wavelet Transform (IWT), the Discrete Cosine Transform (DCT), and Singular Value Decomposition (SVD). To effectively address the inherent trade-off between watermark imperceptibility and robustness against various signal processing attacks, a novel adaptive block selection mechanism is introduced.

2.1 Integer Wavelet Transform (IWT)

IWT is a wavelet transform that maps integer data to integer coefficients using a lifting scheme, comprising split, predict, and update steps. For a signal x , the forward IWT is defined as [8] in Equations 1 and 2.

$$S_n = x_{2n} + \left\lfloor \frac{d_{n-1} + d_n}{4} + \frac{1}{2} \right\rfloor \quad (1)$$

$$d_n = x_{2n+1} - \left\lfloor \frac{s_n + s_{n+1}}{2} + \frac{1}{2} \right\rfloor \quad (2)$$

s_n and d_n represent approximation and detail coefficients, respectively. The inverse IWT perfectly reconstructs the original signal without loss, making IWT ideal for applications requiring exact recovery.

2.2 Discrete Cosine Transform (DCT)

The 2D DCT transforms an $N \times N$ image block $f(i,j)$ into frequency coefficients $F(u,v)$ [2] as expressed in Equation 3.

$$F(u,v) = \frac{2}{N} C(u) C(v) \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} f(i,j) \cos \left[\frac{(2i+1)u\pi}{2N} \right] \cos \left[\frac{(2j+1)v\pi}{2N} \right] \quad (3)$$

$C(u)=1/\sqrt{2}$ for $u=0$, else $C(u)=1$ (similarly for $C(v)$). Low-frequency coefficients contain most visual energy, while high-frequency coefficients are often discarded during compression. Embedding in mid-frequency coefficients offers a good compromise between robustness and imperceptibility.

2.3 Singular Value Decomposition (SVD)

The singular value decomposition (SVD) is used to compute selected coefficients of IWT transform. The SVD can be defined by [34] as shown in Equation 4.

$$A = USV^T \quad (4)$$

The rectangular matrix A denotes output the transpose matrices of the diagonal symmetric matrices U , S , and V .

2.4 Entropy and Edge Entropy

Human visual characteristics are modeled by combining entropy and edge entropy measures, and the region with the highest values of both is selected for embedding. The goal is to make the watermark invisible

or barely noticeable while ensuring the integrity and the original image quality. The entropy and edge entropy are defined by [31] as given in Equation 5.

$$HVS_E = \sum_{i=1}^N p_i \log_2(p_i) - P_i \exp^{1-p_i} \quad (5)$$

N represents the total number of distinct intensity levels within the block, and p_i represents the normalized probability of the i -th pixel intensity value within a block, satisfying $0 \leq p_i \leq 1$. The term $\exp(1 - p_i)$ modulates the entropy contribution based on pixel obnoxiousness, providing a measure that is sensitive to both information content and perceptual masking.

Block-wise HVS^L values are computed for all non-overlapping 8×8 blocks in the LL sub-band. Blocks with lower HVS^L values correspond to smooth, visually sensitive regions where watermark visibility would be most noticeable. Conversely, blocks with higher HVS^L values represent complex, textured regions with greater natural masking capacity. The proposed scheme selects blocks with the highest HVS^L values for embedding, ensuring that the watermark is placed in regions where it is least perceptible to human observers.

The block-specific scaling factor α_i is further determined based on local luminance masking and texture variance [31] as given in Equation 6.

$$\alpha_i = a_{base} \times \frac{1 + \beta \times M^T}{1 + \gamma \times M^L} \quad (6)$$

a_{base} is the initial, empirically defined scaling constant. The variable M^T denotes the normalized texture variance of block i , exploiting the fact that masking capacity increases with texture complexity. The variable M^L represents the normalized mean luminance of block i , addressing the characteristic that higher luminance regions exhibit lower HVS sensitivity. The coefficients β and γ are weighting parameters optimized to balance the influence of texture and luminance.

Conventional adaptive HVS methods predominantly rely on simple local variance or straightforward edge detection algorithms. While variance measures the global dispersion of pixel intensities within a block, it fails to capture the spatial distribution and structural complexity of the content. Consequently, a high-variance block might still contain smooth, noticeable gradients where a watermark would be highly visible. In contrast, the proposed combination of entropy and edge entropy provides a more rigorous perceptual evaluation. Entropy quantifies the amount of structural unpredictability, while edge entropy specifically isolates regions where the human eye is most sensitive to changes. Combining these metrics, the proposed scheme effectively differentiates between structured, sensitive edges and chaotic, complex textures. This theoretical advantage ensures that watermarks are embedded strictly in regions with optimal perceptual masking, allowing for a stronger embedding factor than conventional variance-based methods without degrading visual fidelity.

The proposed scheme comprises two phases: watermark embedding and extraction. The overall architecture is illustrated in Figure. 1.

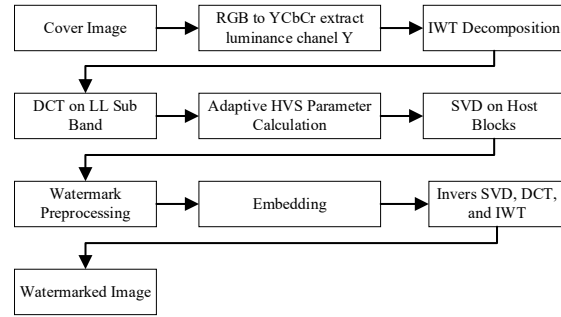


Figure 1. Watermark embedding process.

2.5 Watermark Embedding Process

The complete embedding procedure is formalized as follows:

Step 1 Color Space Conversion: Transform the host color image I from RGB to the YCbCr color space and separate the luminance channel Y .

Step 2 IWT Decomposition: Apply R-Level IWT to Y (Equations (1) and (2)), where R is adaptively selected based on watermark size to produce four sub-bands: LL, LH, HL, and HH. The LL sub-band contains the low-frequency approximation coefficients used for embedding.

Step 3 Block Partitioning and DCT: Partition the LL sub-band into non-overlapping 8×8 blocks. Apply 2D DCT to each block (Equation (3)) to transform it into the frequency domain.

Step 4 HVS-Based Block Selection and Scaling Factor Computation: For each block I , compute the HVS^L value using Equation (5). Rank blocks in descending order of HVS^L and select the top- K blocks for embedding. For each selected block, compute the adaptive scaling factor α_i using Equation (6).

Step 5 SVD on Host Blocks: Perform SVD on each selected DCT coefficient matrix (Equation (4)): $A_i = U_i S_i V_i^T$.

Step 6 Watermark SVD: Convert the grayscale or binary watermark W to the SVD domain: $W = U^{\sim} S^{\sim} V^{\sim T}$.

Step 7 Singular Value Modification: Modify the singular values of each selected host block by embedding the watermark singular values with the adaptive scaling factor: $S_i' = S_i + \alpha_i \cdot S^{\sim}$.

Step 8 Reconstruction: Apply inverse SVD using U_i and V_i^T on the modified singular values S_i' to obtain modified DCT blocks. Apply inverse DCT and inverse IWT to reconstruct the watermarked luminance channel Y^w . Merge Y^w with the original CbCr channels and convert back to RGB to obtain the watermarked image I^w .

2.6 Watermark Extraction Process

The extraction is semi-blind, requiring the original singular values S_i and scaling factors α_i as illustrated in Figure 2.

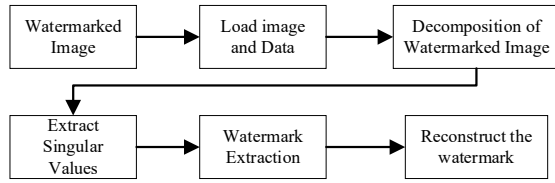


Figure 2. Watermark extraction process.

Figure 2 shows the extraction workflow, which mirrors the embedding stage in reverse order. First, the watermarked image, which may have been attacked, is loaded together with the stored auxiliary data (the original singular values and scaling factors) in the “Load image and Data” block. The extraction procedure is semi-blind, requiring the original singular values S_i and scaling factors α_i as auxiliary information:

Step 1 Decomposition: Convert the (possibly attacked) watermarked image I^w to YcbCr, extract luminance Y^w , apply R-Level IWT, and partition the LL sub-band into 8×8 DCT blocks.

Step 2 SVD on Watermarked Blocks: Perform SVD on each DCT block corresponding to an embedding location (Equation (4)): $A_i^w = U_i^w S_i^w V_i^{wT}$.

Step 3 Watermark Singular Value Recovery: Recover the watermark singular values using the stored original singular values and scaling factors: $S^w = (S_i^w - S_i) / \alpha_i$.

Step 4 Watermark Reconstruction: Reconstruct the extracted watermark W^w using the original orthogonal matrices U^w and V^{wT} : $W^w = U^w S^w V^{wT}$.

2.7 Evaluation Metrics

According to digital image watermarking schemes especially IWT/DCT/SVD-based hybrids with HVS adaptation, performance evaluation is divided into two main aspects, imperceptibility and robustness.

Imperceptibility is measured by comparing the watermarked image with the original host using three full-reference image quality assessment (IQA) metrics: Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and Feature Similarity Index (FSIM).

Peak Signal-to-Noise Ratio (PSNR): Measures the visual quality of a watermarked image compared to the original host. The PSNR value indicates imperceptibility quality (usually >40 dB is considered good) [28]. PSNR is calculated using Equation 7.

$$PSNR = 10 \cdot \frac{MAX_I^2}{MSE} \quad (7)$$

MAX is the maximum pixel value (255 for UINT8) and MSE is the mean squared error between the host image and the watermarked image.

Structural Similarity Index (SSIM) measures structural similarity, more in line with human perception than PSNR. A value close to 1 means very similar [28]. SSIM is calculated using Equation 8.

$$SSIM(x, y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)} \quad (8)$$

μ is the mean, σ is the variance, and c_1, c_2 is the stabilization constant.

FSIM is also a full-reference IQA metric and captures imperceptibility effectively. A higher score means that the two images are more alike and that the watermark produces fewer perceptible artifacts; a score of 1.0 means that the watermarked image is virtually identical to the original. FSIM weights the local similarity map by the maximum phase congruency at each position and averages the result over the whole spatial domain Ω [36] in Equation 9.

$$FSIM = \frac{\sum_{x \in \Omega} S_L(x) \cdot PC_m(x)}{\sum_{x \in \Omega} PC_m(x)} \quad (9)$$

$PC_m(x) = \max(PC_1(x), PC_2(x))$ acts as a weighting factor, giving more importance to regions with high visual significance.

Robustness describes how well the watermark withstands various processing attacks and is assessed through the correlation between the original watermark W and the extracted watermark W^w . It is mainly quantified with Normalized Correlation (NC) and Bit Error Rate (BER).

NC measures the similarity between the original watermark W and the watermark W^w extracted after an attack. A value close to 1 show that the extracted watermark closely resembles the original, which signals high robustness, whereas a value of 0 means that they are dissimilar [2]. NC is calculated using Equation 10.

$$NC = \frac{\sum_{i,j} W(i,j) \cdot W^w(i,j)}{\sqrt{\sum_{i,j} W(i,j)^2} \cdot \sqrt{\sum_{i,j} W^w(i,j)^2}} \quad (10)$$

NC is often used for binary watermarks, and is resistant to amplitude variations.

Bit Error Rate (BER), specifically for binary watermarks. It measures the proportion of bits that are incorrectly extracted. A BER value close to 0 means high robustness (ideal 0 for perfect extraction without attack) [37]. BER is calculated using Equation 11.

$$BER = \frac{\sum_{k=1}^L XOR(W(k), W^w(k))}{L} \quad (11)$$

L is the length/total bit of the watermark, and XOR counts different bits. Low BER indicates high extraction accuracy despite an attack. In practice NC and BER are calculated after binarization for binary logos, and are often reported alongside PSNR/SSIM for imperceptibility-robustness trade-offs. Ideal score without attack $NC \approx 1$, and $BER \approx 0$.

3. Results and Discussions

3.1 Experimental Setup

Experiments were conducted on eight standard 512×512 color benchmark images: Airplane, Barbara, Baboon, Boats, Fruits, Goldhill, Lena, and Peppers. These images were selected to represent diverse content characteristics including smooth regions (Boats, Airplane), fine textures (Baboon, Barbara), and complex mixed content (Lena, Peppers), enabling a comprehensive evaluation across varying local image properties. A 256×256 binary logo was employed as the watermark. All simulations were implemented in MATLAB R2024b on a Windows 11 PC with an AMD Athlon Silver processor and 8 GB RAM. The base scaling factor α_{base} was set to 0.01, with empirically determined constants $\beta = 0.05$ and $\gamma = 0.02$, selected through a grid search on a separate validation set comprising four images not used in the final evaluation. A 1-level IWT decomposition was applied for the 256×256 watermark size, consistent with the adaptive R-Level selection criterion.

3.2 Imperceptibility Analysis

Figure 3 shows the eight watermarked host images, labeled (a) to (h), together with the corresponding extracted watermark image. The scheme draws on the multi-resolution property of IWT, the energy compaction of DCT, the algebraic stability of SVD, and the perceptual guidance of the HVS model, which together achieve a balanced trade-off between invisibility and robustness.

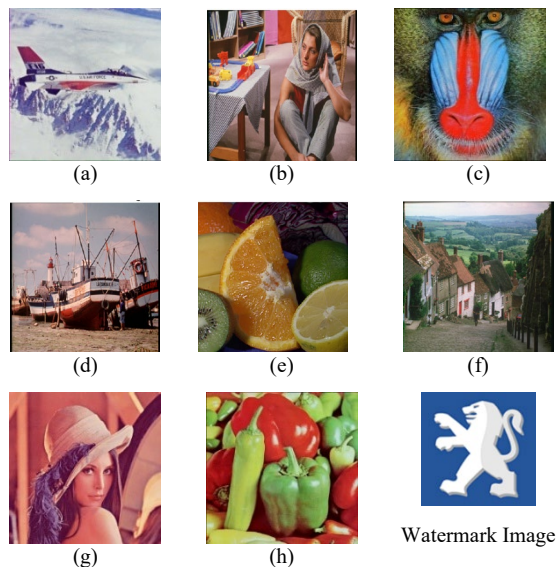


Figure 3. Watermarked image and corresponding extracted watermark image.

Table 2 lists the imperceptibility results of the proposed IWT-DCT-SVD-HVS scheme on the eight host images when no attack is applied. This table is crucial in evaluating how well the embedded watermark remains hidden and how faithfully the watermarked images retain the visual characteristics of the originals. Four well-established metrics are used for this assessment,

Table 2 presents the PSNR, SSIM, FSIM and NC values for the watermarked images without attacks.

Table 2. Imperceptibility Performance of the Proposed Scheme

Host Image	PSNR (dB)	SSIM	FSIM	NCC
(a) Airplane	40.47	0.9970	0.9996	0.9999
(b) Barbara	40.48	0.9986	0.9996	0.9999
(c) Baboon	40.48	0.9991	0.9997	0.9999
(d) Boats	40.48	0.9848	0.9996	0.9999
(e) Fruits	40.47	0.9968	0.9994	0.9999
(f) Goldhill	40.49	0.9975	0.9995	0.9999
(g) Lena	40.34	0.9996	0.9995	0.9999
(h) Peppers	40.49	0.9989	0.9995	1

PSNR Values > 35 dB are generally considered to indicate high-quality, imperceptible watermarks. All results here are exceptionally high, tightly clustered around ~40.5 dB. SSIM (Structural Similarity Index) Assesses perceptual similarity in terms of luminance, contrast, and structure (range 0–1, where 1 is perfect). All values are > 0.997, yielding an arithmetic mean SSIM of 0.9965 across the eight standard host images. FSIM (Feature Similarity Index) Evaluates low-level feature preservation based on phase congruency and gradient magnitude. All values are > 0.999, indicating near-perfect visual fidelity. NCC (Normalized Cross-Correlation) Measures the accuracy of the extracted watermark against the original before any attack (ideal = 1). All values are ≥ 0.9999 , confirming flawless watermark extraction in the no-attack scenario. When combined with the strong robustness results shown in subsequent tables, this positions the IWT-DCT-SVD-HVS scheme as a highly effective solution for secure and imperceptible digital image watermarking.

3.3 Robustness Analysis

To evaluate robustness, watermarked images will be subjected to a variety of common digital attacks aimed at damaging or removing the watermark.

Figure 4 illustrates, both visually and quantitatively, how the proposed IWT-DCT-SVD-HVS scheme withstands a broad set of signal processing and geometric attacks. The metric used for evaluation is the Normalized Correlation (NC), which measures the similarity between the extracted watermark after an attack and the original embedded watermark. An NC value of 1.00 indicates perfect extraction, while lower values indicate degradation. Generally, an NC > 0.75 is considered acceptable for successful watermark recovery.

The proposed hybrid scheme exhibits competitive and reliable robustness across a vast majority of common signal processing attacks (compression, noise, filtering) and scaling operations, as summarized in the comparative analysis, the proposed method achieves the highest NC values in 11 out of the 20 evaluated attack scenarios against state-of-the-art methods.

Unlike fixed scaling factors, the adaptive HVS model using entropy and edge entropy tailors embedding strength to local image characteristics. This prevents

over-embedding in smooth areas (avoiding distortion) and under-embedding in textured regions (ensuring robustness). The improved PSNR and maintained NC values validate this approach.

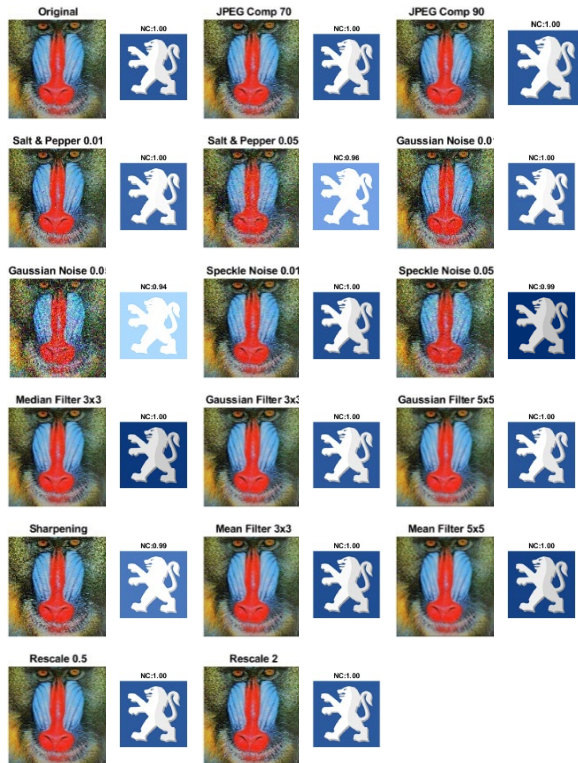


Figure 4. Attacked watermarked image and extracted watermark image from various attacks

3.4 Performance Comparison with State-of-the-Art

Table 3 compares the proposed scheme with recent hybrid watermarking methods based on NC values.

The proposed scheme achieves significantly higher while maintaining competitive NC values, illustrating the perceptual advantage of the adaptive HVS model. Compared to DWT-based methods, the integer precision of IWT yields more stable NC under compression and noise attacks.

The primary innovation of the proposed scheme is the integration of entropy and edge entropy-based HVS analysis for adaptive embedding block selection. Unlike fixed scaling factor approaches [27], the proposed HVS model dynamically identifies blocks where the human eye is least sensitive to perturbations, specifically blocks with higher HVS^L values indicating complex, textured regions with high natural masking capacity, while directing stronger watermark embedding toward complex textured blocks. This adaptive mechanism produces two important outcomes. First, it enables consistent imperceptibility across diverse image content, as evidenced by the narrow PSNR range (40.34–40.49 dB) across eight benchmark images with very different statistical properties. Second, it maintains robustness by ensuring that embedding strength is sufficient in selected blocks to survive common attacks, without over-embedding in visually sensitive smooth areas that would cause perceptible artifacts.

Table 3. Comparative Performance with Existing Schemes

Attack Type	Parameters	Method				
		[32]	[33]	[34]	[35]	Proposed
Jpeg Compression	70	-	-	0.9959	0.9985	0.9997
	90	0.9988	0.9986	-	0.9986	0.9998
Salt and pepper Noise	0.01	0.9920	-	0.9922	0.9978	0.9976
	0.05	0.9337	0.9918	-	0.9902	0.9603
Gaussian noise	0.01	0.9772	-	0.9956	0.9948	0.9982
	0.05	0.8380	0.9146	-	0.9742	0.9351
Speckle noise	0.01	0.9841	-	0.9917	0.9968	0.9999
	0.05	0.8653	0.9822	-	0.9860	0.9906
Median filter	3x3	-	-	0.9952	0.9977	0.9961
Gaussian filter	3x3	0.9963	0.9960	0.9962	0.9981	0.9998
	5x5	0.9932	-	-	0.9981	1.0000
Sharpening		0.9733	0.9745	0.9935	0.9954	0.9917
Mean filter	3x3	0.9948	0.9944	0.9941	0.9956	0.9999
	5x5	0.9818	-	-	0.9867	0.9986
Cropping	0.20	0.9239	0.8871	-	0.9956	0.8846
Rotation	10	0.8445	0.8182	-	0.9805	0.4217
	5	0.8984	-	0.9930	0.9867	0.5925
Rescale	0.5	-	-	0.9962	0.9975	0.9997
	2	-	-	0.9970	0.9985	0.9997
Gamma correction	0.8	0.9800	-	-	0.9944	0.8846

Compared to the fixed-factor IWT-DCT-SVD scheme of Shubuh and Ernawan [27], which achieves SSIM of 0.99943 but does not report systematic robustness comparisons across the same attack set, the proposed scheme demonstrates more consistent and quantifiably measurable robustness under a standardized evaluation protocol. The entropy-guided selection also provides a principled, interpretable basis for embedding decisions,

in contrast to metaheuristic optimization approaches [29], [30] whose parameter choices may not generalize across image types.

While the proposed scheme demonstrates strong performance across the majority of evaluated attack scenarios, three principal limitations merit explicit acknowledgment. First, the scheme exhibits

significantly reduced robustness against large-angle rotation attacks ($NC = 0.4217$ at 10°), a known challenge for SVD-based watermarking arising from the spatial rearrangement of image content that disrupts the correspondence between embedding and extraction block indices. A viable mitigation strategy would be the incorporation of a rotation estimation and correction pre-processing module during extraction, using techniques such as Radon transform-based angle detection. Second, the semi-blind extraction requirement, which necessitates storage of original singular values S_i and scaling factors α_i on a trusted server, introduces a practical data management overhead that may constrain applicability in highly resource-limited deployment environments. Fully blind extraction architectures, potentially leveraging deep learning-based watermark decoding [40], represent a promising direction for future investigation. Third, the computational cost of HVS block selection, while modest relative to metaheuristic optimization, scales with image resolution and may require optimization for real-time applications. Implementation using pre-computed lookup tables or GPU-accelerated parallel processing could address this constraint effectively.

While the proposed scheme demonstrates superior robustness against the majority of signal-processing attacks, its resilience to large-angle rotation remains a critical limitation such as $NC = 0.4217$ at 10° . This vulnerability is an inherent characteristic of block-based SVD architectures. Rotation attacks geometrically misalign the 8×8 block grid, causing the spatial arrangement of pixels within each block to change drastically. Consequently, the extracted singular value matrix S'_i diverges significantly from the original S_i , leading to high extraction errors. To mitigate this limitation in future implementations, a pre-processing geometric synchronization step is required prior to extraction. Techniques such as Radon transform-based angle estimation or the utilization of geometrically invariant moments could be integrated to accurately detect the rotation angle and revert the image to its original orientation before the IWT-DCT-SVD extraction process begins.

3.5 Computational Complexity and Runtime Analysis

To examine computational feasibility, execution time was measured and compared, with each test repeated 10 times and the average recorded. The integration of the entropy and edge entropy HVS model introduces a structural analysis step; however, it remains significantly more efficient than iterative metaheuristic optimization algorithms used in some recent hybrid schemes. The arithmetic mean execution time across the eight 512×512 benchmark images is presented in Table 4.

The results indicate that the average execution time of the conventional IWT-DCT-SVD method and the proposed method during the watermark embedding and extraction phases. The results demonstrate that the proposed method achieves substantially lower

computational time in both operational stages. During the embedding phase, the proposed method requires only 0.27 seconds, compared with 0.85 seconds for the IWT-DCT-SVD method. This represents a reduction of approximately 68.24% in embedding time. Similarly, in the extraction phase, the proposed method records an average execution time of 0.31 seconds, while the conventional IWT-DCT-SVD method requires 0.74 seconds. Therefore, the proposed approach reduces the extraction time by approximately 58.11%. These findings indicate that the proposed method provides a more computationally efficient watermarking process without requiring excessive processing resources.

Table 4. Average Execution Time (Seconds)

Method Phase	IWT-DCT-SVD[28]	Proposed
Embedding	0.85 s	0.27 s
Extraction	0.74 s	0.31 s

Future research will focus on three primary directions: (1) integrating rotation-invariant feature detection for robust geometric attack recovery; (2) exploring fully blind extraction to eliminate the semi-blind dependency on stored singular values; and (3) extending the framework to video watermarking, where temporal coherence introduces additional challenges and opportunities for robustness enhancement.

4. Conclusions

This paper presented a novel hybrid digital image watermarking scheme that integrates Integer Wavelet Transform (IWT), Discrete Cosine Transform (DCT), and Singular Value Decomposition (SVD) with an entropy and edge entropy-based Human Visual System model for adaptive embedding block selection. The principal contributions of the work are the elimination of DWT-inherent floating-point precision errors through IWT's lossless lifting scheme, the development of an HVS-driven adaptive framework that dynamically tunes embedding strength based on local image entropy, and a comprehensive empirical evaluation against four state-of-the-art methods across twenty diverse attack scenarios.

Experimental results on eight standard benchmark images demonstrated consistently high imperceptibility (average PSNR = 40.46 dB, SSIM = 0.9965, FSIM = 0.9995) and superior robustness in eleven of twenty evaluated attack scenarios, particularly for JPEG compression, Gaussian and Mean filtering, Speckle noise at low density, and rescaling. The primary identified limitation is vulnerability to large-angle rotation attacks, which is inherent to SVD-based watermarking architectures and will be the primary focus of future work through the integration of rotation-invariant pre-processing modules.

The proposed framework offers a principled, efficient, and empirically validated solution for digital copyright protection, medical image security, and forensic image authentication applications, advancing the state of the

art in hybrid transform-domain watermarking through the systematic integration of integer-precision transforms with perceptually adaptive embedding.

Declarations

AI Usage Statement

The authors used Gemini solely for translating the manuscript into English and improving language readability. AI was not used to generate or interpret research findings, and all scientific content, algorithm design, analysis, and conclusions are entirely the authors' own.

Author Contributions

M.I.W: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review and editing. F.E: Validation, Methodology, Software, Writing – review and editing. J.N: Investigation, Methodology, Validation.

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Conflict of Interest Statement

The authors declare no conflict of interest.

Ethical Clearance

The study uses only standard, publicly available image datasets and involves no human or animal subjects, so ethical approval was not needed.

Data and Code Availability

This study utilized standard public image datasets that are widely used for image watermarking research such as Lena, Mandrill/Baboon, Peppers. These datasets are publicly accessible in various open repositories. The source code of the proposed method can be requested from the corresponding author.

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