An Enhanced Gray-Scale Digital Watermarking Approach Utilizing Discrete Wavelet Transform and Reed-Solomon Error Correction

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Abstract— Digital watermarking has become essential for protecting intellectual property and ensuring content authenticity in the digital age. However, a significant challenge remains in developing watermarking techniques that are both robust against various attacks (such as compression, noise, and cropping) and imperceptible to the human eye, which is crucial for maintaining the quality of the original content. This paper addresses these challenges by proposing an advanced digital image watermarking technique that combines a three-level Discrete Wavelet Transform (DWT) using the Haar wavelet family with Reed-Solomon (RS) error-correcting codes. The three-level DWT decomposes the image into multiple frequency components, allowing the watermark to be embedded in the most significant parts of the image, thereby enhancing robustness. The integration of Reed-Solomon codes over finite fields further increases the watermark's resilience, enabling recovery even when parts of the watermark are damaged or lost due to attacks. Experimental results demonstrate that the proposed approach significantly improves watermark performance, with Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index Measure (SSIM) showing substantial gains. The combination of Haar-based DWT and Reed-Solomon codes improves the watermark's robustness by up to 27 times compared to traditional methods without error correction. This approach provides a promising solution for secure, efficient, and reliable digital watermarking in applications requiring high robustness and content integrity.

Keywords— Discrete Wavelet Transform (DWT), Gray image watermarking, Reed Solomon (R.S.), watermarking embedding, watermarking extraction, Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index Measure (SSIM),Attack(Salt and paper, Gaussian ,Speckle).

الملخص ـ أصبح تضمين العلامات المائية الرقمية أمرًا أساسيًا لحماية الملكية الفكرية وضمان أصالة المحتوى في العصر الرقمي. ومع ذلك، تظل التحديات الرئيسية تتمثل في تطوير تقنيات العلامات المائية التي تكون قوية بما يكفي لمقاومة الهجمات المختلفة (مثل الضغط، والضوضاء، والقص) وفي نفس الوقت غير ملحوظة للعين البشرية، وهو أمر ضروري للحفاظ على جودة المحتوى الأصلي. يعالج هذا البحث هذه التحديات من خلال اقتراح تقنية متقدمة لتضمين العلامات المائية في الصور الرقمية تعتمد على التحويل الموجي المتقطع ثلاثي المستويات (DWT) باستخدام عائلة موجات HAAR إلى جانب أكواد تصحيح الأخطاء من نوع REED-SOLOMON (RS). يقوم التحويل الموجي ثلاثي المستويات بتقسيم الصورة إلى مكونات تردد متعددة، مما يسمح بتضمين العلامة المائية في الأجزاء الأكثر أهمية في الصورة، مما يعزز من قوة العلامة المائية. تعزز إضافة أكواد REED-SOLOMON فوق الحقول المنتهية من مقاومة العلامة المائية، مما يمكنها من التعافي حتى في حالة تعرض أجزاء من العلامة للتلف أو الفقد بسبب الهجمات. أظهرت النتائج التجريبية أن المنهجية المقترحة تحسن أداء العلامة المائية بشكل كبير، حيث أظهرت مقاييس نسبة الذروة للإشارة إلى الضوضاء (PSNR) ومؤشر التشابه البنيوي (SSIM) زيادات ملحوظة. ويعزز الجمع بين تحويل HAAR الموجي وأكواد REED-SOLOMON من قوة العلامة المائية بمقدار يصل إلى 27 ضعفًا مقارنة بالطرق التقليدية التي لا تتضمن تصحيح الأخطاء. تقدم هذه المنهجية حلًا واعدًا لتضمين العلامات المائية الرقمية بشكل آمن وفعال وموثوق في التطبيقات التي تتطلب درجة عالية من القوة وسلامة المحتوى.

الكلمات المفتاحية: *تحويل الموجات المنفصلة (DWT)، العلامات المائية للصورة الرمادية، ريد سولومون (R.S.)، تضمين العلامات المائية، استخراج العلامات المائية، نسبة ذروة الإشارة إلى الضوضاء (PSNR)، مقياس مؤشر التشابه البنيوي (SSIM)، الهجوم (الملح والورق، الغاوسي، البقع).*

I. Introduction

Digital watermarking embeds a digital image into a host image, enabling detection and proving ownership rights, tracking content usage, ensuring authorized access, facilitating content authentication, and preventing unauthorized replication.
[3,1]. Digital watermarking research covers various branches, Figure 1 [2, 7, and 10].
using classification methods like Discrete Fourier Transform, Discrete Cosine Transform, and Discrete Wavelet Transform. Techniques include DFT, DCT, and DWT.
Researchers investigate non-blind watermarking in the transform domain using invisible watermarks and evaluate DWT's effectiveness with Reed-Solomon cyclic error-correcting codes against various attacks. [6, 5, 8, 11, 9]. The remainder of this paper is organized as follows:

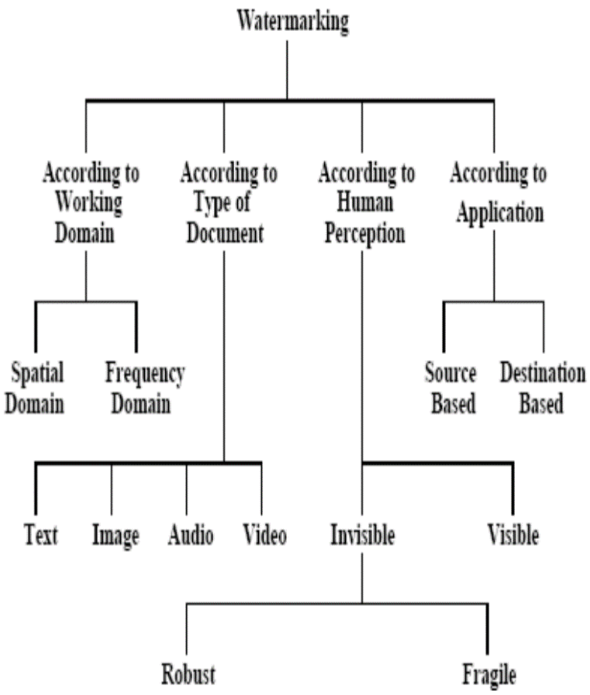


Figure 1: Watermarking Classification

II. Literature Review

Research in digital watermarking is related to many subjects in the area of computer science, such as image processing, communication theory, and encryption. In addition to data hiding and steganography science, all these related subjects will be covered in this research. As a result of the importance of digital watermarking in solving the problems of protecting the copyrights of owners or publishers in digital media, there are numerous studies that have suggested using error control coding techniques to correct the possible errors caused by the attacks on the digitally marked image [1, 2, 3, 4, 5, 6].
It has motivated the researcher to contribute to this field by investigating the effects of the well-known error correction codes, the Reed-Solomon code, and DWT domain embedding and extracting algorithms. The study aims to increase the robustness of image watermarks.

As mentioned previously, the transformation of products from physical to digital requires the development of methods and algorithms to address intellectual perceptual problems, in particular the copyright problem. The good solution is a combination of digital watermarking (visible/invisible mark) methods and error correction coding (ECC) methods, which protect copyright [7, 8, 9, 10, 11, 12].
Many models and algorithms have been designed to address copyright problems. Numerous papers and research about the digital watermarking techniques are proposed to solve some watermarking problems, and other research focuses on the error correction code concept [15, 16, 17, and 18].
More specific research articles that are very closely related to the research topic are given below for completeness.
Details of This study presents invisible, blind, and robust color image watermarking algorithms using wavelet transform and error-correcting codes. These algorithms are designed to be robust against attacks like JPEG compression, noise, and color. Reed-Solomon codes are used to improve robustness, with Sudan's algorithm showing good performance against hue and saturation attacks [4, 18, 19, 20].
A new digital image watermarking algorithm uses Reed-Solomon codes and rank metric codes for attack resistance, complementing other random error watermarking strategies like JPEG compression. [24, 25, 27].

The study examines the impact of various Reed-Solomon codes, including 15 and 31, on the robustness of image watermarks, focusing on five of them and their embedding method.
The study investigates Discrete Wavelet Transform (DWT) sensitivity against various attacks on watermarked images, revealing that the Reed-Solomon code outperforms other codes.
[26, 18, 30].
The proposed digital watermarking method utilizes DWT and DCT techniques to embed and extract copyright protection, resulting in a hybrid approach for two-dimensional images.
[18].

Mathematical Preliminary & State of the Art

A. Discrete Wavelet Transform

The wavelet transform is a sophisticated mathematical tool widely used across various applications, particularly in image processing and watermarking [20,6]. The core concept of the Discrete Wavelet Transform (DWT) is to decompose an image into its frequency components using wavelets of varying frequencies and limited durations. During each level of decomposition, the DWT separates the image into four sub-bands:
The wavelet transform creates four sub-bands:
1-LL (Low-Low),
2-HL (High-Low),
3-LH (Low-High),
and 4-HH (High-High).
The LL sub-band captures lower-resolution approximations of the image, while the LH sub-band focuses on vertical detail. The LL sub-band can be further decomposed to achieve additional detail levels. [13,9,23] .

B. Reed Solomon:

Reed-Solomon (RS) codes are error-correcting codes used in digital communication systems and storage devices, notably for correcting burst errors in CDs, DVDs, QR codes, and satellite communications [15,18.20].

Key Concepts of Reed-Solomon Codes:

1. Block Codes: Reed-Solomon codes are block codes, meaning that data is divided into fixed-size blocks, and each block is encoded separately. In each block, a certain number of bits are added as redundancy to help detect and correct errors.
2. Symbols and Field Arithmetic: Unlike binary codes (which work with individual bits), Reed-Solomon codes work with symbols. A "symbol" is typically a group of bits (e.g., 8 bits = 1 byte, or 1 symbol = 8 bits in a common implementation). The key part is that Reed-Solomon codes are based on arithmetic over finite fields, specifically Galois fields.

- For an RS code, the finite field typically used is the field of polynomials modulo an irreducible polynomial. The field can have size q = 2mq = 2^mq = 2m, where mmm is an integer and q is the number of possible symbols in the field.
- In simpler terms, instead of just using binary arithmetic (0 or 1), the symbols are drawn from a larger set of values.

3. Parameters: A Reed-Solomon code is usually denoted as RS(n, k), where:
   - n is the total number of symbols in the encoded block (length of the codeword).
   - k is the number of data symbols (original message).
4. Encoding and Decoding:
   - **Encoding**: The data is transformed into a codeword by adding redundancy (parity symbols) based on a set of mathematical operations in the finite field.
   - **Decoding**: When the data is received, the decoder uses the parity symbols to detect and correct errors. The most common decoding algorithm is the **Berlekamp-Massey algorithm**, which efficiently finds errors in received codewords.
5. Error Detection and Correction:

- Because the code is designed to detect patterns of errors in the data, even if multiple symbols are corrupted, it can correct a certain number of errors without needing to request retransmission. This is particularly useful for applications like satellite communication or optical media, where retransmission is costly or impractical. [30.26.25]

Advantages of Reed-Solomon Codes:

- Error correction: Can correct multiple errors in data blocks, especially burst errors.
- Flexibility: The parameters n and k can be chosen depending on the application, allowing for customizable error-correction strengths.
- Efficiency: Well-suited for practical implementation in hardware and software. [31].

III. Proposed Methodology

The overall Digital Watermarking System, consists of the following:

A. Digital Watermarking Embedding:

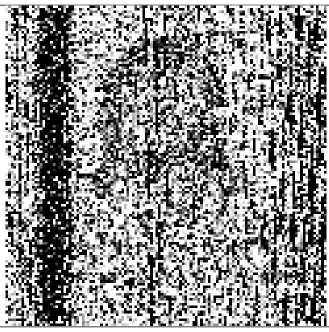
The study uses a non-blind watermarking approach, embedding a digital watermark into a host image using RS block error correcting codes and multilevel DWT. The embedding is performed using the alpha blending technique, transforming the host image directly.

$$WMI = k \times (LL_j) + q \times (EWM_j) \quad (1)$$

Where :

- EWM_j is the j^{th}-level The text describes a method for obtaining a low frequency approximation of the encoded watermark image.
- LL_j is the j^{th}-level The text describes a method for obtaining a low frequency approximation of the host image. HI.
- WMI is the watermarked image.
- k & q are the scaling factors. :
- Scaling factor k= r controls the strength of the watermark.
- Scaling factor q influences the intensity or distortion caused by the watermark embedding.
- The optimal values of r = 0.99 and q=0.001 are chosen after experiments to balance imperceptibility and robustness, making sure the watermark survives attacks while maintaining the quality of the original image.
- $j = 1,2,3$ levels in DWT.

Table.1: Determination of Extensive experiments were conducted to determine the optimal values for the scaling factors r and q.

r and q variable	Watermark Image	Watermarked Image	Note
r= 0.99 **q=0.001**			Optimal Value
r= 0.2 **q=0.01**			Worst case

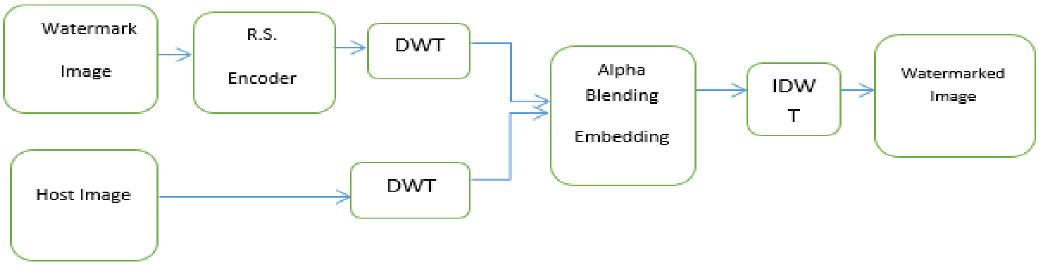


Figure 2: Watermarking Embedding

As mentioned above, two steps need more explanation:
1- RS encoding of the digital watermark image and the DWT level for both the encoded digital watermark and the host image. RS Encoding of the Digital Watermark
The encoding using length n=255 RS block codes depends on the arithmetic of finite fields GF (256) , so the digital watermark image is converted to binary digits and then to Galois field elements to be able to encode the information symbols to codewords. This is illustrated in figure (2).
2-Multilevel DWT of the encoded digital watermark & host image
The alpha blending technique for embedding the encoded digital watermark in the host image is done in the DWT transform domain.

Table 2.Digital Watermark Image Encoding Steps

Read the digital watermark image (WM)
Convert to binary bits stream
Form the GF(256) Galois field symbols
Divide into blocks of size k symbols
Call RS Encoder (n, k) to obtain the n length codeword for each k symbols
Convert to binary stream
Obtain the encoded digital watermark image (EWM)

This table outlines the steps for Watermarking Image Encoding (WME) using Reed-Solomon, further illustrated in the following figure.

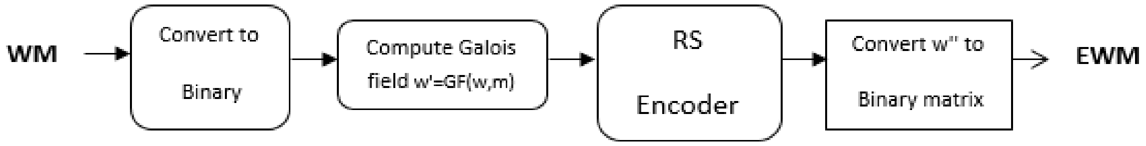


Figure 3: Watermark Image Encoding

B. Performance Evaluation & Measures

Non-blind digital watermarking systems avoid distortion, where the digital watermark image(WMI) doesn't affect the host image's appearance(HI), as per the Peak Signal to Noise ratio.

$$SNR = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} HI^2(i,j)}{\sum_{i=1}^{M}\sum_{j=1}^{N} [HI(i,j)-WMI(i,j)]^2} \quad (2)$$

And ,

$$PSNR_{dB} = 10 * \log_{10}\frac{\sum_{i=1}^{M}\sum_{j=1}^{N} HI^2(i,j)}{\sum_{i=1}^{M}\sum_{j=1}^{N} [HI(i,j)-WMI(i,j)]^2} \quad (3)$$

Digital watermarking systems' copy write protection requires successful extraction despite severe attacks, using similarity between inserted and extracted watermarks, as outlined in Structured Similarity Image Value (SSIM).

$$SSIM = \frac{(2\mu_x\,\mu_y+c_1)(2\sigma_{xy}+c_2)}{(\mu_x^2+\mu_y^2+c_1)(\sigma_x^2+\sigma_y^2+c_2)} \quad (4)$$

Where "μ", "σ", & "σ_{xy}" The mean, variance, and covariance of the digital watermark image and the recovered digital watermark image are being analyzed.

. "c_1", "c_2" The stabilizing constants in images range from 0 to 1, with similar images having an SSIM value near 1.

C. Attacks on the Watermarked Image:

In this subsection, the various types of attacks on the watermarked image will be presented. Three main categories of attacks are considered:

a. Addition of noise attack

a-Salt & Pepper noise: J = imnoise(I,'salt & pepper',d) .The command adds salt and pepper noise to image I, affecting approximately d*numel(I) pixels, with a default of 0.05.

b-Gaussian noise: J = imnoise(I,'gaussian',M,V). The command adds Gaussian white noise with a mean of m and variance of v to the image I, defaulting to zero mean noise and 0.01 variance.

c-Speckle noise: J = imnoise(I,'speckle',v). The command adds multiplicative noise to an image using the equation J = I + n * I, where n is uniformly distributed random noise with mean 0 and variance v.

D. Digital Watermark Extraction

In this research, various types of attacks on the watermarked image are considered. Addition of noise was the focus of this research; the noise types considered are salt & pepper, Gaussian, and speckle noise. In this subsection, the extraction of the digital watermark method is presented and illustrated. Watermark Extraction Using Alpha Blending Extraction Technique: Let denote the attacked digital watermarked image. The formula of the alpha blending extraction technique is as follows:

$$ERW = (WMI_A - k \times LL_j)/q \quad (5)$$

Where :

- ERW is the low frequency approximation of the recovered encoded watermark.
- LL_j is the j^{th}-level low frequency approximation of the host image HI.
- WMI_A is the attacked watermarked image.

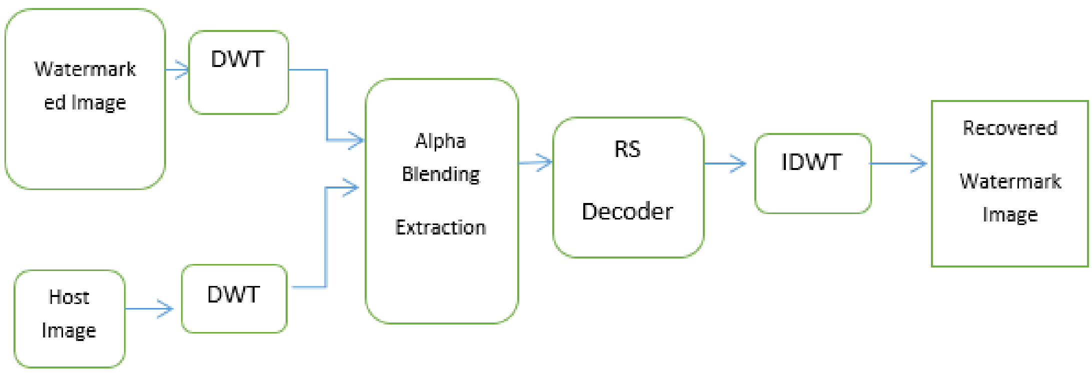


Figure 4: Watermark Extraction

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In figure (5), the decoded digital watermark is obtained, so in order to obtain the recovered digital watermark image, a decoding step are to be performed as given below:

Table 3. Digital Watermark Image Decoding Steps

Read the encoded digital watermark image (EWM)
Convert to binary bits stream
Form the GF(256) Galois field symbols
Divide into blocks of size n symbols
Call RS Decoder (n, k) to obtain the k length information symbols
Convert to binary stream
Obtain the decoded digital watermark image (DWM)

This table shows the steps for Watermarking Image Decoding (WMD), and these steps are shown by the figure following.

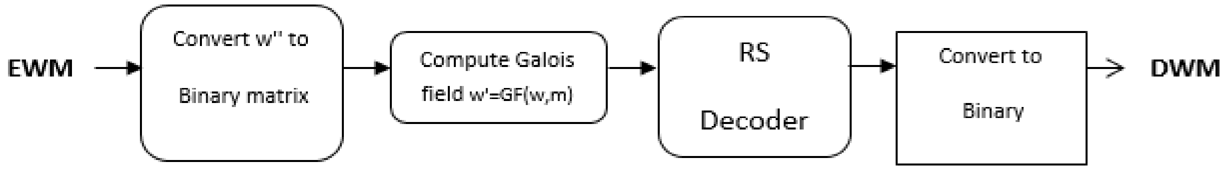


Figure 5: Watermark Image Decoding

IV. Experimental setup & Demonstration of Watermark Embedding

This table shows the watermark used in this paper along with its host image and the process of embedding it to obtain the watermarked image.

Table 4: Kinds of images that using in this paper:

Host image	Watermark image	Watermarked image
		

DWT (Discrete Wavelet Transform) is often used to embed watermarks into images at various levels of decomposition. The "DWT level" refers to the number of times the wavelet transform is applied to break down the image into different frequency sub-bands (low- and high-frequency components).

Types of attacks refer to methods that attempt to degrade, remove, or alter the watermark, such as noise addition, compression, cropping, or filtering. The effectiveness of these attacks varies depending on the DWT level used for watermark embedding. Higher DWT levels can provide more robustness against attacks, as the watermark is embedded deeper within the image's frequency components, making it harder for attackers to remove or distort it without significant degradation of the host image.

Table 5: Type of attack with DWT level

DWT _level SALT & PEPPER ATTACK	DWT _level - GAUSSIAN NOISE ATTACK	DWT _level SPECKLE NOISE ATTACK

A. Peak Signal Nosie Ratio (PSNR)

PSNR (Peak Signal-to-Noise Ratio) is a commonly used metric to measure the quality of an image before and after any processing, such as the application of attacks in watermarking. It compares the original image to the modified one (e.g., after watermark embedding or after an attack) by calculating the ratio between the maximum possible pixel value and the noise introduced due to the alteration. A higher PSNR value generally indicates that the modified image retains more similarity to the original, suggesting better quality. In the context of watermarking, PSNR is used to assess the distortion in the host image before any attacks are applied, with higher PSNR values indicating that the watermarking process has caused minimal visual distortion to the image. As shownin Table 6, the image before the attack likes Salt and Paper, Gaussian, and Speckle.

Table 6: PSNR for before Attack types

Noise	**Images Without R.S. before attacks**		
	PSNR before Salt and Paper Attack	PSNR before Gaussian Attack	PSN before Speckle Attack
	PSNR	PSNR	PSNR
0.001	46.5680	46.5680	46.5680
0.01	46.5680	46.5680	46.5680
0.1	46.5680	46.5680	46.5680

PSNR (peak signal-to-noise ratio) after an attack type measures the quality of the image after it has undergone some form of tampering or distortion, such as noise addition (salt and pepper, Gaussian, or speckle). In the context of image watermarking, this metric helps evaluate the impact of the attack on both the host image and the embedded watermark. A lower PSNR value after an attack indicates more degradation in image quality, meaning the watermark or the host image has been significantly affected. It reflects how resistant the watermark is to the applied attack, with higher PSNR values after an attack suggesting that the watermark remains intact and the image quality is still good. As shown in the table 7 image after the attack with R.S.

Table 7: PSNR for after Attack type

Noise	**Images With R.S. after attacks**		
	With R.S. after Salt and paper attack	With R.S. after Gaussian attack	With R.S. after Speckle attack
	PSNR	PSNR	PSNR
0.001	33.324	33.6678	33.6678
0.01	32.345	33.541	33.541
0.1	32.123	32.345	32.345

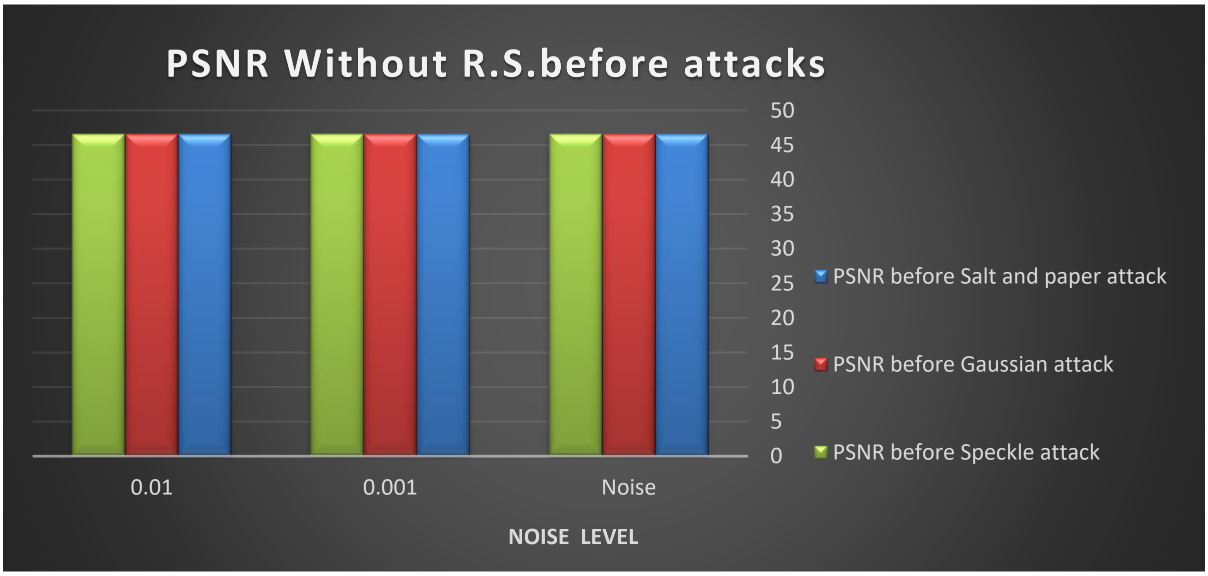


Figure 6: PSNR without R.S. before Attacks

This Figure shows PSNR before an attack this measures the quality of the original image before it undergoes any alterations or attacks.

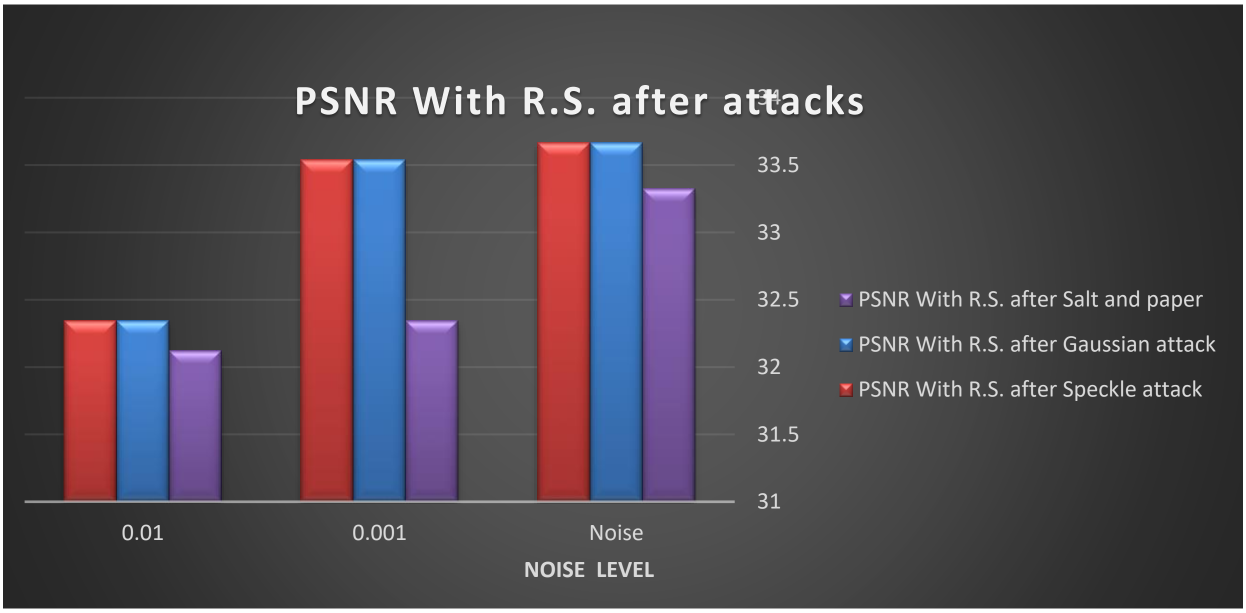


Figure 7: PSNR with R.S. after attacks

This figure shows PSNR with R.S. (reversible watermarking scheme). After attacks, it measures the quality of the watermarked image and the effectiveness of the watermarking technique after it has been subjected to various attacks. A lower PSNR value indicates that the image quality and watermark integrity have been significantly degraded, while a higher PSNR value suggests that the watermark is more resistant to the attack and the image quality has been largely maintained.

B. Similarity Structure Index Measurement (SSIM)

SSIM (Structural Similarity Index) after an attack measures the perceived quality of the image after it has undergone some form of tampering or distortion, such as noise, compression, or cropping. Unlike PSNR, which focuses on pixel-wise differences, SSIM evaluates changes in structural information, luminance, contrast, and texture, which are more aligned with human visual perception. After an attack, SSIM provides a better understanding of how the attack has impacted the overall visual quality of the image and the watermark. A lower SSIM value indicates significant degradation, meaning the attack has caused visible damage to the image or watermark, while a higher SSIM value suggests that the image and watermark remain visually similar to the original, even after the attack. In this case, a noise of type Salt & Pepper, Gaussian, or Speckle is added to the watermarked image with different levels. Table 8 and Figure 8 show the values of SSIM after extracting the watermark image for each noise DWT level for the case with RS block code.

It can be observed that using Reed-Solomon (RS) codes results in approximately a threefold improvement in performance at the noise levels of Salt and Pepper (0.001, 0.1), with values of (0.9977, 0.434). For Gaussian noise (0.001, 0.1), the values are (0.9865, 0.5235), and for Speckle noise (0.001, 0.1), the values are (0.9725, 0.5532). This illustrates, through bar plots, the significant increase in Structural Similarity Index Measure (SSIM) when using RS codes across various noise levels. Show that in table 8.

Table 8: SSIM for after Attack type

Noise Level	**Images With R.S. after Attacks**		
	SSIM after Salt And Paper attacks	SSIM after Gaussian attacks	**SSIM after Speckle attacks**
0.001	0.9977	0.9865	**0.9725**
0.01	0.8733	0.8763	**0.8588**
0.1	0.434	0.5235	**0.5532**

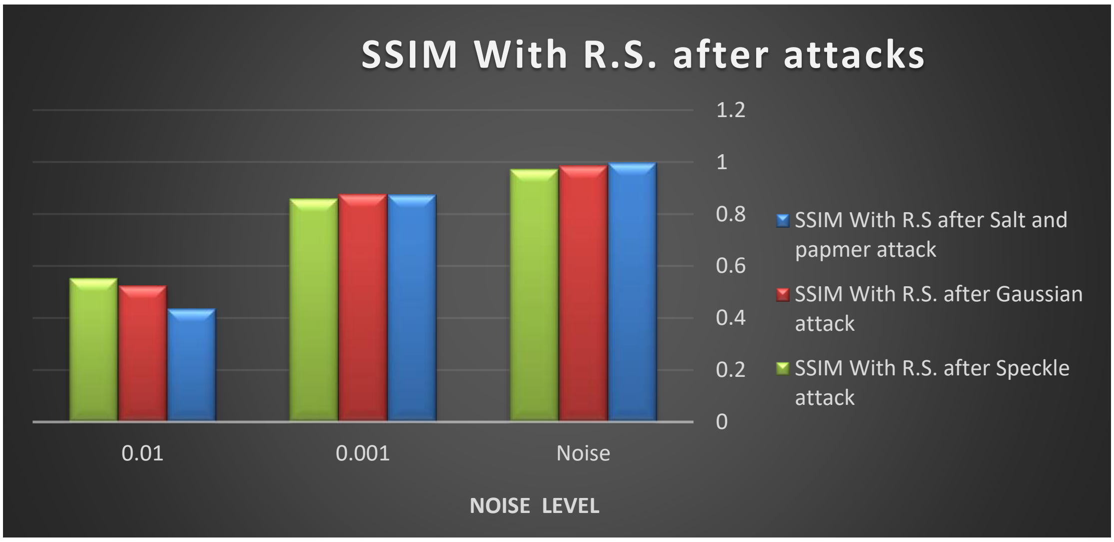


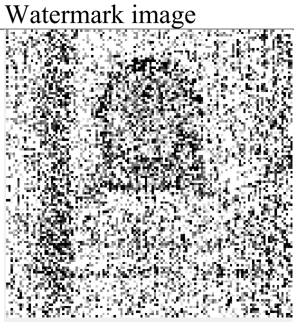
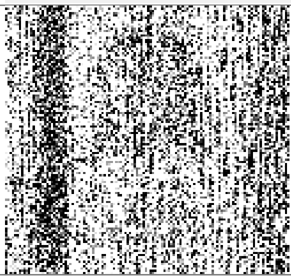
Figure 8: SSIM with R.S. after attacks

SSIM (Structural Similarity Index) after an attack evaluates the visual quality of an image after it has been subjected to distortions such as noise, compression, or cropping. Unlike PSNR, which measures pixel-based differences, SSIM focuses on how structural elements like luminance, contrast, and texture are perceived by the human eye. After an attack, SSIM provides a more accurate assessment of the image's overall visual integrity and the preservation of the watermark. A lower SSIM value indicates that the attack has significantly degraded the image, making it appear noticeably distorted, while a higher SSIM value suggests that the image and watermark have been well-preserved, retaining a high degree of similarity to the original, as shown in figure 8.

V. Experimental setup & Demonstration of Attacks on the Watermarked Image

In the following, we demonstrate the watermarked image method for attack without R.S. The one case of that is DWT level is used and three cases of attacks (Salt and Paper, Gaussian, and Speckle). The results indicate that when noise is present without R.S., the images are unclear and distorted. However, when R.S. is present, the images are clearer and of higher quality. Yet, at a value of 0.1, they begin to lose clarity by 60%. The results are as shown below.

Table 9: Gray images in Salt and Paper attack

Gray image Salt and Paper Attack				
Noise level	Image without Reed Solomon		**Image with Reed Solomon**	
	Host Image	Watermark image	Host image	**Watermark image**
0.001				
0.01				

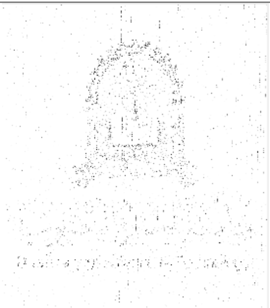
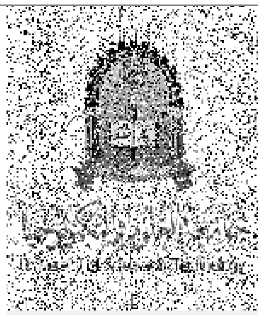
0.1				

Table 10: Gray images in Gaussian attack

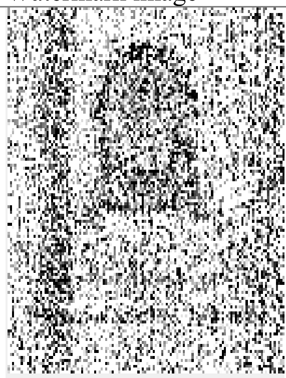
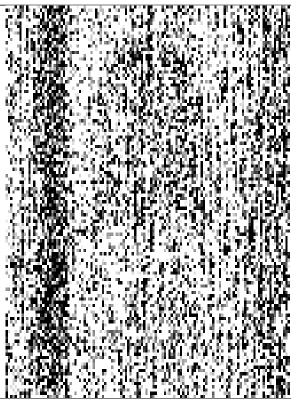
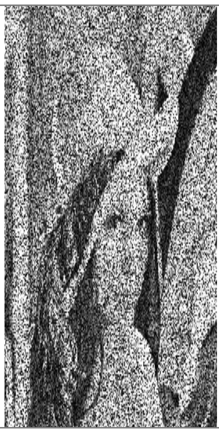
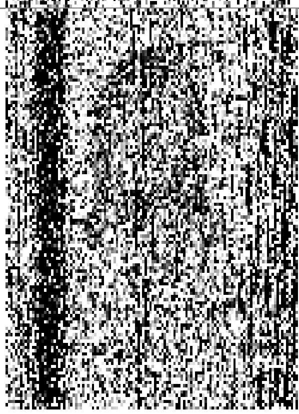
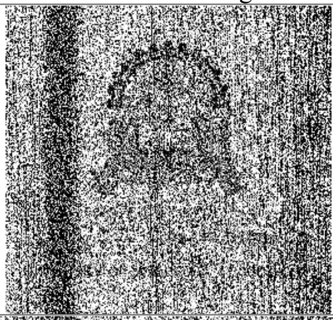
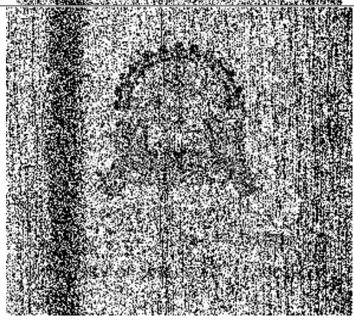
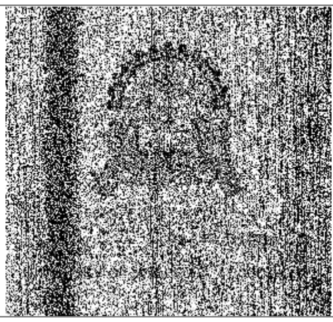
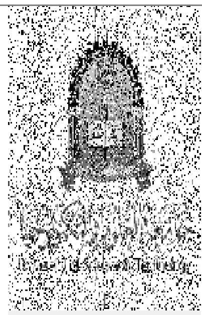
Gray image Gaussian Attack				
Noise level	Image without Reed Solomon		**Image with Reed Solomon**	
	Host Image	Watermark image	Host image	**Watermark image**
0.001				
0.01				
0.1				

Table 11: Speckle images in Speckle attack

Gray image Speckle Attack				
Noise level	Image without Reed Solomon		**Image with Reed Solomon**	
	Host Image	Watermark image	Host image	**Watermark image**
0.001				
0.01				
0.1				

VI. Conclusion

This paper presents an enhanced digital watermarking technique that combines Discrete Wavelet Transform (DWT) with Reed-Solomon (R.S.) codes to improve the robustness and quality of watermarking in digital images. The proposed methodology effectively embeds watermarks in significant frequency components, ensuring minimal distortion to the host image. Experimental results demonstrate substantial improvements in performance metrics such as Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index Measure (SSIM), particularly in scenarios involving various noise attacks. The integration of error-correcting codes, specifically Reed-Solomon codes, significantly enhances the resilience of the watermark against attacks, achieving robustness improvements up to 27 times compared to systems without such codes. The findings highlight the effectiveness of using a three-level DWT in conjunction with R.S. codes, making this approach a promising solution for secure digital watermarking applications.

7- Future work could explore further optimizations of the embedding process and the application of this technique to a broader range of multimedia content, enhancing copyright protection and content authentication in digital media.

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