# The Evolution of Spatial Domain Digital Watermarking and Steganalysis: A Comprehensive Review of Robust Frameworks

Adithya Gopalakrishnan
*Department of Computer Science and Engineering(Cyber Security)*
*Vimal Jyothi Engineering College*
Chemperi, Kannur
Email: agk58565@gmail.com

***Abstract*—In the era of rapid digital transmission and ubiquitous multimedia sharing, ensuring copyright protection, authenticity, and data integrity has become a critical challenge. Digital watermarking serves as a primary solution by embedding hidden information directly into host media. This paper focuses on the spatial domain, which is favored for its computational efficiency, simplicity, and high imperceptibility compared to frequency-domain techniques. We explore a variety of advanced methodologies, including the use of pixel-based saliency maps to identify visually insignificant regions for embedding, and histogram equalization to maximize data-hiding capacity by redistributing pixel intensities. Furthermore, specialized frameworks are discussed for the protection of cultural heritage images and reversible data hiding (RDH) for sensitive information. To complement these security measures, we examine state-of-the-art steganalysis using optimized Convolutional Neural Networks (CNNs) designed to detect hidden payloads with high accuracy. Collectively, these advancements aim to resolve the inherent trade-offs between robustness, imperceptibility, and embedding capacity in digital security systems.**

***Index Terms*—Digital Watermarking, Spatial Domain, Steganalysis, Imperceptibility, Robustness, Saliency Map, Histogram Equalization, Cultural Heritage Protection, Convolutional Neural Networks (CNN).**

## I. Introduction

The proliferation of internet technologies and digital networks has transformed the way multimedia content is shared, but it has also facilitated unauthorized access, illegal copying, and the tampering of valuable assets. To mitigate these risks, digital watermarking has emerged as a robust mechanism for certifying ownership and validating data authentication. By hiding ”watermarks” within digital content, owners can verify the provenance of an image or audio file without degrading its perceptual quality.

Watermarking techniques are broadly categorized into frequency-domain and spatial-domain approaches. While frequency-domain methods like Discrete Cosine Transform (DCT) offer high robustness, spatial-domain methods—which involve directly altering pixel values—are increasingly researched for their lower computational costs and superior transparency. Modern spatial techniques leverage Human Visual System (HVS) characteristics by using saliency maps and edge detection (such as the compass edge detector) to pinpoint regions where modifications are least noticeable to the human eye. This field also encompasses specialized applications, such as the ownership verification of colored cultural heritage images through DC coefficient modification and the use of prediction-error expansion for large-scale reversible data hiding. Parallel to the development of embedding techniques is the field of steganalysis, which utilizes advanced machine learning architectures to identify and quantify hidden data, ensuring a balanced ecosystem of information security and forensic capability.

## II. Literature Survey

Samrah Mehraj [1] presents a blind and robust watermarking scheme specifically designed for the ownership verification of colored Cultural Heritage (CH) images1111. Operating in the spatial domain, the method utilizes DC coefficient modification and the ”Y” (luminance) element of the YCbCr color space for watermark insertion. The ”Y” element is divided into non-overlapping $8 \times 8$ blocks, which are then split into two $4 \times 8$ subblocks. Rather than using the traditional Discrete Cosine Transform (DCT), the authors independently calculate DC coefficients in the spatial domain by determining the mean of the pixel intensities. Watermark bits are inserted by altering these coefficients so that the coefficient of the odd-location subblock is greater than the even-location one for a bit ”1,” and vice versa for a bit ”0”. Experimental results show an average Peak Signal-to-Noise Ratio (PSNR) of 40.0830 dB and a structural similarity index (SSIM) close to one, ensuring the high imperceptibility and robustness of the technique against various signal-processing attacks.

Tohari Ahmad [2] proposes a new approach within a Convolutional Neural Network (CNN) to improve the accuracy of detecting hidden confidential data in spatial domain images. The primary contribution is the optimization of local features during the feature extraction stage. The proposed CNN architecture includes a preprocessing phase using 30 Spatial Rich Model (SRM) filter banks to improve network convergence. It also incorporates an average pooling layer to achieve generalized feature maps, which helps reduce the overfitting issue and significantly improves detection accuracy. The final classification is probabilistic, achieved by supplying the vector outputs of fully connected layers into a softmax function. Testing with the BOSSBase 1.01 dataset showed that the approach improved detection accuracy by 2.1% to 3.6% over previous state-of-the-art models like Zhu-Net and GBRAS-Net.

Houtan Haddad Larijani [3] propose a ”Save Algorithm” for gray scale image watermarking in the spatial domain, chosen for its relatively low calculation complexity compared to domain-transform techniques. This algorithm works through a pixel-by-pixel comparison between the host image and the watermark. If a host pixel's value matches a watermark pixel's value—optionally within a defined threshold T—its position is saved into a row vector (RV) which acts as a secret key. Because the algorithm only saves positions and does not modify the host image's pixel values, it demonstrates high fidelity and complete invisibility. Extraction is equally simple, involving recreating the watermark matrix using the values from the host image at the positions saved in the key. The paper reports robust performance against common attacks like JPEG compression and Gaussian noise, maintaining PSNR values between 20dB and 40dB

Rajesh Kannan Megalingam [4] provides a performance comparison between a novel robust spatial domain digital image watermarking technique and conventional frequency domain methods. The proposed method processes an image in the spatial domain by dividing it into different intensity subsections. Specifically, the pixel intensity matrix is compared against four constants (63, 127, 191, and 255) to classify pixels into four diversified matrices: lowest intensity (LL), intermediate (LH), higher (HL), and highest (HH)21. These matrices are scaled by factors $\alpha$ and $\beta$ to embed the watermark. The technique supports both visible and invisible watermarking depending on the scaling factor values. Experimental results using Verilog HDL and Matlab implementation demonstrate that the novel spatial domain method achieves a PSNR of 29.66 dB, which is comparable to the 33.16 dB achieved by frequency-domain DCT-based techniques.

Sidhanta Kumar Balabantaray [5] introduces an improved spatial domain watermarking technique that balances imperceptibility, robustness, and embedding capacity by combining histogram equalization, compass edge detection, and adaptive alpha blending. Compass edge detection is utilized to identify less noticeable regions of an image for watermark placement, as changes in these areas are less perceptible to viewers. Histogram equalization is employed to adjust the distribution of pixel intensities, which enhances the image's contrast and increases its overall data-hiding capacity. The watermark is then integrated into the host image using an adaptive alpha blending technique that calculates the blending effect based on the transparency properties of the objects. Results from the USC-SIPI database indicate that the proposed method ensures high visual transparency with PSNR values near 58.30 dB and provides an average concealing capacity of 3.5615 bits-per-pixel.

Xuping Huang [6] provides a comprehensive survey of audio digital watermarking techniques. It defines digital watermarking as the hidden embedding of information within audio content for purposes like authentication, copyright protection, and tracking. The survey classifies techniques into three primary domains: spatial (including LSB insertion and spread spectrum), frequency (DWT and DCT), and time-frequency (STFT and Wavelet transforms). It highlights the necessity of balancing four key attributes: invisibility, robustness, security, and payload capacity. For instance, it notes that while spatial domain techniques like LSB insertion are simple and offer high capacity, they are fragile and sensitive to common processing operations like filtering. Conversely, frequency domain methods provide greater robustness but can be more complex. The paper concludes by noting that as digital audio evolves, these insights will guide the development of more resilient and efficient content protection systems.

Gang Wang [7] describe a rapid and robust color image watermarking technique that operates in the spatial domain while leveraging frequency domain advantages. The core methodology involves discussing the DC coefficient of a 2D-DFT obtained directly in the spatial domain without performing a true transform. This DC coefficient is used to embed and extract the watermark through a proposed quantization technique. To ensure security, the 24-bit color watermark is permuted using the Arnold transform, and embedding blocks are selected via a Hash pseudorandom scrambling algorithm. Experimental results across the CVG-UGR and USC-SIPI databases show average PSNR values exceeding 35 dB and SSIM values near 1. The system also demonstrates a total processing time of only 0.7239 seconds, which is faster than several related frequency-domain methods. The paper concludes that the proposed method is highly effective for copyright protection due to its strong robustness against common attacks like JPEG compression and cropping while maintaining a high real-time feature.

Shuai Li [8] proposes an improved Reversible Data Hiding (RDH) algorithm based on Prediction-Error Expansion (PEE) for large-capacity data hiding in the spatial domain. The methodology partitions the carrier image into two areas: a shadow area for the first layer of embedding and a blank area that can accommodate up to three additional layers. A refined predictor is used to calculate prediction errors for all pixels except boundary ones, and these errors are used to generate a prediction-error histogram (PEH). Secret information is then embedded by expanding and shifting this PEH. A key result of the study is that the method achieved a large embedding capacity (up to 130,050 bits) while keeping distortion and computing complexity low. At a capacity of 20,000 bits, the average PSNR remained higher than 3.52 dB compared to state-of-the-art methods. The authors conclude that their I-PEE method effectively resolves the inherent contradiction between payload capacity and image distortion.

Subreena Mushtaq [9] proposes a spatial domain-based blind and robust watermarking scheme specifically for the ownership verification of colored Cultural Heritage (CH) images. The proposed methodology utilizes the luminance (Y) element of the YCbCr color space. The host image's Y component is divided into $8 \times 8$ non-overlapping blocks, which are further split into $4 \times 8$ subblocks. Instead of using a traditional Discrete Cosine Transform (DCT), the authors independently calculate DC coefficients in the spatial domain by determining the mean of pixel intensities. Watermark bits are then inserted by altering these coefficients so that one becomes greater than the other depending on the bit value. The results show an average PSNR of 40.0830 dB and a Structural Similarity Index (SSIM) value close to one under no attack, ensuring the technique's imperceptibility. The scheme also demonstrates robust resistance to simultaneous and singular signal-processing attacks. The paper concludes that this method offers lower computational complexity than frequency-domain techniques, making it suitable for real-time CH image protection.

Manas Ranjan [10] presents a spatial domain digital image watermarking framework designed to balance the trade-off between robustness and imperceptibility. The methodology utilizes a pixel-based saliency map to identify less visible areas of an image, where alterations by the human visual system (HVS) remain less noticeable. It further employs histogram equalization to redistribute pixel intensity values, which improves image clarity and helps locate suitable areas for concealing confidential data. The watermark is then embedded into the host image using an adaptive alpha blending technique, which distributes data across the image to enhance hiding capacity and security. Experimental results demonstrate that the method achieves high visual transparency, with Peak Signal to Noise Ratio (PSNR) values ranging from 50 to 52 dB. The framework also shows an average hiding capacity of 4.302 bits per pixel (bpp) and maintains strong resilience against various attacks, including JPEG compression and noise addition. The authors conclude that integrating histogram equalization with saliency maps effectively enhances embedding capacity and ensures resilience against visual distortions.

## III. Conclusion

The collective research presented across these papers highlights a significant paradigm shift toward advanced spatial domain digital watermarking, demonstrating that it can effectively rival frequency-domain techniques in both robustness and imperceptibility. By utilizing innovative strategies such as DC coefficient modification performed directly in the spatial domain, researchers have achieved frequency-level resilience with significantly lower computational overhead, making these methods ideal for real-time applications such as ownership verification for cultural heritage images. The integration of Human Visual System (HVS) characteristics through pixel-based saliency maps, entropy analysis, and compass edge detection allows for the adaptive embedding of watermarks in regions with minimal visibility, thereby maximizing data capacity while maintaining high visual transparency. Collectively, these studies conclude that spatial domain frameworks, reinforced by adaptive alpha blending and intelligent feature optimization, provide a highly reliable, efficient, and secure foundation for modern digital authentication and intellectual property protection.

## References


[1] S. Mehraj, S. Mushtaq, S. A. Parah, K. J. Giri, J. A. Sheikh, A. H. Gandomi, M. Hijji, and K. Muhammad, "Spatial domain-based robust watermarking framework for cultural images," *IEEE Access*, vol. 10, pp. 117 248–117 260, 2022.

[2] N. J. de La Croix and T. Ahmad, "Toward hidden data detection via local features optimization in spatial domain images," in *2023 Conference on Information Communications Technology and Society (ICTAS)*, 2023, pp. 1–6.

[3] H. H. Larijani and G. R. Rad, "A new spatial domain algorithm for gray scale images watermarking," in *2008 International Conference on Computer and Communication Engineering*, 2008, pp. 157–161.

[4] R. K. Megalingam, M. M. Nair, R. Srikumar, V. K. Balasubramanian, and V. S. V. Sarma, "Performance comparison of novel, robust spatial domain digital image watermarking with the conventional frequency domain watermarking techniques," in *2010 International Conference on Signal Acquisition and Processing*, 2010, pp. 349–353.

[5] S. K. Balabantaray, M. R. Nayak, B. Panda, M. K. Gourisaria, A. Basu, and T. H. Sardar, "An improved image watermarking technique in spatial domain using histogram equalization and compass edge detection with adaptive alpha blending technique," in *2025 4th OPJU International Technology Conference (OTCON) on Smart Computing for Innovation and Advancement in Industry 5.0*, 2025, pp. 1–8.

[6] U. H. Panchal and R. Srivastava, "A comprehensive survey on digital image watermarking techniques," in *2015 Fifth International Conference on Communication Systems and Network Technologies*, 2015, pp. 591–595.

[7] Q. Su, D. Liu, Z. Yuan, G. Wang, X. Zhang, B. Chen, and T. Yao, "New rapid and robust color image watermarking technique in spatial domain," *IEEE Access*, vol. 7, pp. 30 398–30 409, 2019.

[8] S. Li, L. Hu, C. Sun, L. Chi, T. Li, and H. Li, "A reversible data hiding algorithm based on prediction error with large amounts of data hiding in spatial domain," *IEEE Access*, vol. 8, pp. 214 732–214 741, 2020.

[9] S. Mehraj, S. Mushtaq, S. A. Parah, K. J. Giri, J. A. Sheikh, A. H. Gandomi, M. Hijji, and K. Muhammad, "Spatial domain-based robust watermarking framework for cultural images," *IEEE Access*, vol. 10, pp. 117 248–117 260, 2022.

[10] M. R. Nayak, B. Panda, P. K. Mallick, A. K. Jena, and B. Sahoo, "Spatial domain image watermarking framework using pixel-based saliency map and histogram equalization," in *2025 International Conference on Emerging Systems and Intelligent Computing (ESIC)*, 2025, pp. 164–171.