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Enhanced image compression through hybrid staggered downsampling and DCT

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ABSTRACT

Image compression is crucial for multimedia applications with the aim of reducing storage and/or transmission costs, while preserving reliable visual quality. In this research, we propose a novel hybrid image compression technique based on staggering downsampling combined with discrete cosine transform (DCT). The proposed approach not only overlaps downsample images to reduce data redundancy but also utilizes the energy compaction properties of DCT for efficient compression. The proposed method performance on benchmark grayscale images such as Lena, House, and other refernce images were evaluated by means of image quality assessment metrics, namely, peak signal-to-noise ratio (PSNR), structural similarity index (SSIM), visual information fidelity (VIF); and compression efficiency metrics: bitrate and compression ratio. The results clearly show that the proposed algorithm outperforms JPEG and Set partitioning in hierarchical trees (SPIHT) + discrete wavelet transform (DWT) method, with the following results: PSNR of 45.02, MSSIM of 0.9856, VIF of 0.8271, Bitrate of 0.12 bpp and a Compression Ratio of 64.00 (i.e. a reduction of 64 times). The suggested hybrid image compression method optimizes bug multimedia storage and transmission by minimizing storage space and bandwidth usage while maintaining image quality. It, therefore, achieves a balance between perceptual quality and compression efficiency, making it the best option for resource-constrained applications such as remote sensing, embedded systems, video compression, and medical image archival.

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1. INTRODUCTION

The rapid advancements in digital imaging technologies has resulted in an ever-increasing demand for efficient image compression methods in various fields, mainly medical imaging, remote sensing, multimedia applications, and real-time communications. High-resolution images and videos require a great deal of storage space and a lot of bandwidth. In an ntshell, image compression has become an important aspect of modern digital systems. The ideal image compression algorithm results in a high compression ratio while also providing efficient perceptual quality that guarantees visual quality by yielding important visual detail. Traditional image compression algorithms that use image compression methods like JPEG [1], [2] and SPIHT+DWT [3], [4], are employed due to their simplicity, low computational-complexity and widespread usage. JPEG based on the discrete cosine transform (DCT) is the most commonly used lossy compression standard, however, it produces blocking artifacts and can cause the loss of fine detail, especially when compression ratios are elevated. Set partitioning in hierarchical trees (SPIHT) [5] has proved its efficiency in improving compression efficiency and scalability, when combined with the discrete wavelet transform (DWT). Nonetheless, SPIHT+DWT has its pitfalls too; it oversamples fine details and creates ringing artifacts near edges, resulting in a low perceived visual quality, and it is widely known that the tradeoff between compression efficiency and visual fidelity is the ever-present dilemma in image compression research.

To overcome these challenges, hybrid methods that implement spatial preprocessing combined with transform coding have been examined. Staggered downsampling, or quincunx subsampling, is a potentially efficient method for eleminating data redundancy while preserving salient structural information [6]. Compared uniform sampling, staggered downsampling effectively retains the image geometric structure by only sampling pixels in a staggered manner. The method operates using spatial correlation between neighboring pixels to reduce reduced data size sufficiently while providing minimal degradation. Texture coding with DCT results in a solid hybrid compression when utilized with staggered downsampling. The DCT is usually utilized in image and video compression due to its energy compaction because most of the energy of the signal is concentrated on a few low-frequency coefficients [7]-[9]. This property is efficient since the DCT may be quantized and subsequently entropy-coded [10] to result in maximum compression performance. Coupling staggered downsampling and DCT not only decreases data rates, but also maintains enough fidelity to minimize artifacts while achieving good compression performance through high compression ratios.

This study thoroughly assesses the efficiency of the proposed hybrid image compression method on benchmark datasets. Its results are compared with widely used compression techniques, including JPEG, SPIHT+DWT, and wavelet-based compression, to prove the efficiency of staggered downsampling combined with DCT. The findings illustrate the clear balance between compression efficiency and visual quality provided by this approach. Additionally, this study offers valuable potential to achieve the trade-off between compression ratio and perceptual accuracy. It therefore, contributes to the development of more advanced image compression algorithms for various real-world applications.

2. PROPOSED METHOD

The hybrid image compression approach proposed in this study combines staggered downsampling with the DCT to reach a balance between compression ratio, perceptual quality, and computational complexity at an effective level. Within this framework, spatial preprocessing minimizes local redundancy while transform-based coding utilizes frequency-domain compaction, therefore enabling more efficient representation of image content.

To trace the progression of the image processing pipeline in Figure 1, the outline below represents step from input to output during the compression phase. Below are the general steps that illustrate the proposed method:

- Preprocessing: converting image to grayscale for simplicity.
- Staggered downsampling: reducing image resolution to achieve compression at the expense of losing some information.
- Block Division: dividing the image into smaller blocks (8x8) for DCT processing.
- DCT: applying DCT to each block to reach the frequency domain and compress the image, in other words, quantizing the DCT coefficients and reducing precision to achieve greater compression.
- Reconstruction: applying IDCT to the quantized coefficients to reconstruct each block from the frequency domain back to the spatial domain.
- Interpolation: resizing the image to its original size by means of bilinear interpolation to counteract the downsampling.
- Evaluating the compression quality (PSNR [11]-[16], MSSIM [17]-[18], FIV [19], [20]) and Storage Metrics (Bitrate [21], [22] and compression ratio [23]-[25]) and displaying both the original and resulting images for comparison.

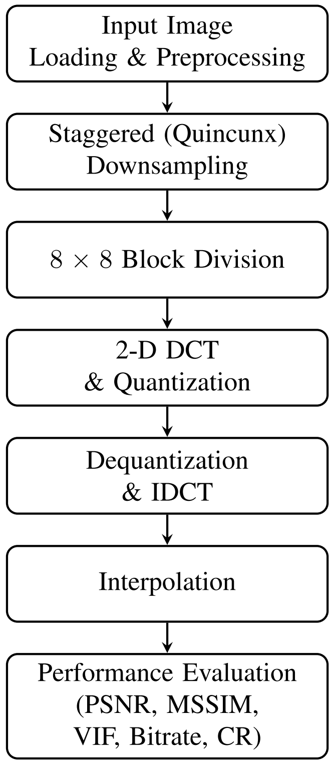

Figure 1. Flowchart of the proposed hybrid image compression method

2.1. Staggered downsampling

Also known as checkerboard or quincunx sampling [7], [8], staggered downsampling structures image pixels along a diagonal grid, thereby preserving important structural information such as edges and textures, while minimizing resolution. This method is particularly helpful for image compression and multi-resolution analysis, as it preserves perceptual quality while reducing data redundancy.

The process comprises three main stages:

– Pixel Selection: Pixels selected in a staggered manner establish a quincunx pattern in which every other pixel in a 2×2 neighborhood is kept. In an 8×8 block, for example, only a reduced number of pixels is kept, yet important detail is maintained.
– Reduction in Resolution: Eesolution is diminished in both horizontal and vertical directions, usually leading to an image reduced by a factor of four (2×downsampling in both directions).
– Structural Information and Related Quality: The method efficiently preserves key structural information, hence, retaining important visual information in the image, therefore increasing the quality of the compressed and reconstructed image.

For example, in the case of an image $I(x, y)$ of size $M \times N$, the staggered downsampled image $I_d(x', y')$ is obtained by sorting one pixel from each 8×8 block as shown in Figure 2. The transformation can be mathematically expressed as follows:

$$I_d(x', y') = I(8x, 8y) \tag{1}$$

where:

- $x' = 0, 1, \ldots, \frac{M}{8} - 1$
- $y' = 0, 1, \ldots, \frac{N}{8} - 1$

This process deceases image resolution by a factor of 8, meaning that the resulting image comprizes only $\frac{1}{8}$th of the initial data.

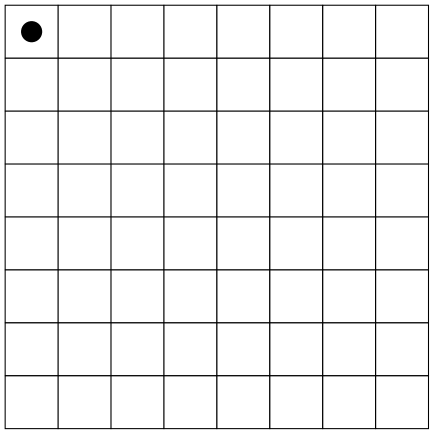

Figure 2. Checkerboard sampling: One pixel selected per 8×8 block (black dot)

2.1.1. Discrete cosine transform

The DCT is a mathematical technique that converts a signal or an image from the spatial domain into the frequency domain [8], [9], expressing a finite set of data samples as a combination of cosine waves with varying frequencies. In the field of image processing, the DCT is commonly employed for compression purposes, as it represents the signal or image efficiently since most of the image's energy is concentrated in a limited number of low-frequency components, which are perceptually more important.

3. RESULTS AND DISCUSSION

The proposed approach was evaluated using well-known benchmark grayscale images such as Lena, House, and others, and was compared with established compression techniques including JPEG and SPIHT combined with the DWT. To evaluate its performance, several objective assessment metrics were employed, namely peak signal-to-noise ratio (PSNR), Structural similarity index measure (SSIM), visual information fidelity (VIF), bit rate (bits per pixel – bpp), and compression ratio. These metrics offer a more comprehensive view of reconstruction quality and coding efficiency by capturing pixel-level accuracy, perceptual resemblance, and compression performance across the evaluation criteria. The bit rate indicates the quantity of information preserved per pixel after compression, whereas the compression ratio reflects the extent to which the original data size has been reduced.

The Tables 1, 2, and 3 present a summary of the results obtained by the proposed method in comparison with JPEG and SPIHT+DWT, using the image quality metrics PSNR (Table 1), MSSIM (Table 2), and VIF (Table 3) across a set of benchmark images.

Table 1 indicates that the proposed algorithm consistently achieves higher PSNR values than JPEG and SPIHT+DWT across all test images. PSNR is expressed in decibels (dB) and functions as an objective indicator of image reconstruction quality, where higher values signify reduced distortion and closer similarity to the original image. For instance, the "Lena" image attains a PSNR of 38.78 dB using the proposed approach, compared with 35.96 dB for SPIHT+DWT and 35.81 dB for JPEG. Substantial improvements are also recorded for the "House" image (45.02 dB) and the "Cameraman" image (42.44 dB), and these results highlight the effectiveness of the proposed algorithm in reconstructing images while preserving structural and textural information. Even in the case of complex and highly textured images such as "Mandril" (34.15 dB) and "Pirate" (37.58 dB), which pose challenges to conventional compression methods due to their high-frequency richness, the proposed algorithm surpasses both SPIHT+DWT (33.17 dB) and JPEG (27.89 dB) in terms of overall reconstruction quality. The results presented in Table 1 reveal the capability of the proposed hybrid scheme to efficiently capture and reconstruct fine image details by leveraging principles from both the spatial and frequency domains.

In Table 2, the MSSIM comparison among the proposed method, JPEG, and SPIHT+DWT is presented. The proposed approach consistently achieved the highest MSSIM values for all tested images, illustrating its effectiveness in combining perceptual and structural image quality. For example, the "House" image attained an MSSIM of 0.9856 with the proposed method, whereas JPEG achieved 0.9749 and SPIHT+DWT reached 0.9473. Even for structurally complex images with rich textures, such as “Mandril” and “Peppers,” the proposed scheme produced MSSIM values of 0.9555 and 0.9297, compared with JPEG values of only 0.8693 and 0.8109. These results provide strong evidence, in line with the PSNR findings, that the proposed scheme delivers high numerical accuracy and visually superior quality, making it particularly suitable for applications prioritizing structural preservation and human perceptual fidelity.

Table 1. PSNR (dB) comparison for the proposed method, JPEG and SPIHT+DWT

Image	Proposed method	JPEG	SPIHT+DWT
Lena	38.78	35.81	35.96
House	45.02	42.13	36.87
Lake	36.58	33.16	34.42
Jetplane	40.03	36.58	36.62
Mandril	34.15	27.89	33.17
Livingroom	37.19	33.34	34.93
Peppers	34.67	28.09	33.97
Pirate	37.58	33.29	35.39
Cameraman	42.44	38.88	37.76
Walkbridge	35.69	30.17	33.86

Table 2. MSSIM comparison for the proposed method, JPEG and SPIHT+DWT

Image	Proposed method	JPEG	SPIHT+DWT
Lena	0.9467	0.9191	0.9060
House	0.9856	0.9749	0.9473
Lake	0.9409	0.8970	0.9066
Jetplane	0.9650	0.9446	0.9297
Mandril	0.9555	0.8693	0.9385
Livingroom	0.9510	0.9086	0.9174
Peppers	0.9297	0.8109	0.9063
Pirate	0.9540	0.9080	0.9252
Cameraman	0.9781	0.9633	0.9392
Walkbridge	0.9658	0.9011	0.9454

Table 3 provides a comparative assessment of the VIF metric for the proposed method, JPEG, and SPIHT+DWT. VIF evaluates the amount of visual information retained in the compressed image relative to the reference image, making it a robust perceptual quality measure. The proposed technique consistently achieves the highest VIF values across all test images, indicating superior preservation of perceptual content. For example, the “House” image attains a VIF of 0.8271 with the proposed approach, which exceeds the values for JPEG (0.7521) and SPIHT+DWT (0.6976). Even for highly textured and structurally complex images such as “Mandril” and “Peppers,” the proposed method delivers VIF values of 0.6176 and 0.6288, significantly outperforming both JPEG and SPIHT+DWT. These results demonstrate that for applications requiring high-quality image reconstruction, the proposed approach preserves visual fidelity and informative content effectively after compression.

Tables 4 and 5 compare the bit rate (bits per pixel) and compression ratio for the proposed approach, JPEG, and SPIHT+DWT. The proposed scheme maintains a remarkably low and consistent bit rate of 0.12 bpp across all evaluated images, corresponding to a uniform and high compression ratio of 64:1. This consistency highlights the robustness and versatility of the method for a diverse range of images, from relatively smooth ones like “Lena” to highly textured images like “Mandril.” In contrast, JPEG and SPIHT+DWT exhibit substantially higher bit rates and correspondingly lower compression ratios. For instance, for the “Mandril” image, JPEG achieves a compression ratio of 5.67:1, and SPIHT+DWT reaches 1.86:1, whereas the proposed method maintains a 64:1 compression ratio. These findings illustrate the efficiency of the proposed coding technique in significantly reducing both storage and transmission requirements while preserving perceptual quality metrics such as MSSIM and VIF, making it particularly suitable for bandwidth-limited and resource-constrained scenarios.

Table 3. VIF comparison for the proposed method, JPEG and SPIHT+DWT

Image	Proposed method	JPEG	SPIHT+DWT
Lena	0.6788	0.5923	0.5850
House	0.8271	0.7521	0.6976
Lake	0.6605	0.5583	0.5879
Jetplane	0.7154	0.6146	0.6141
Mandril	0.6176	0.4362	0.5791
Livingroom	0.6732	0.5586	0.5936
Peppers	0.6288	0.4492	0.5976
Pirate	0.6804	0.5573	0.6028
Cameraman	0.7665	0.6590	0.6632
Walkbridge	0.6778	0.5257	0.6117

Table 4. Bitrate (bpp) comparison for the proposed method, JPEG and SPIHT+DWT

Image	Proposed method	JPEG	SPIHT+DWT
Lena	0.12	0.64	2.30
House	0.12	0.45	2.06
Lake	0.12	0.89	2.77
Jetplane	0.12	0.66	2.32
Mandril	0.12	1.41	4.31
Livingroom	0.12	0.89	2.74
Peppers	0.12	1.11	3.52
Pirate	0.12	0.86	2.62
Cameraman	0.12	0.57	2.17
Walkbridge	0.12	1.24	3.52

Table 5. Compression ratio comparison for the proposed method, JPEG and SPIHT+DWT

Image	Proposed	JPEG	SPIHT+DWT
Lena	64:1	12.53:1	3.48:1
House	64:1	17.70:1	3.88:1
Lake	64:1	9.03:1	2.89:1
Jetplane	64:1	12.05:1	3.45:1
Mandril	64:1	5.67:1	1.86:1
Livingroom	64:1	8.97:1	2.92:1
Peppers	64:1	7.19:1	2.27:1
Pirate	64:1	9.29:1	3.05:1
Cameraman	64:1	13.99:1	3.68:1
Walkbridge	64:1	6.47:1	2.27:1

As shown in the preceding tables, the experimental results for the images used in this study indicate that the proposed compression method outperforms both JPEG and SPIHT+DWT in all tests. The proposed approach achieves the highest values for objective quality metrics such as PSNR, MSSIM, and VIF, demonstrating its superior ability to preserve image details and structural information. In terms of bit rate and compression ratio, the proposed method also significantly surpasses the other techniques, attaining a uniform bit rate of 0.12 bpp and a compression ratio of 64:1 across all images, while JPEG and SPIHT+DWT reach bit rates of 0.53 bpp and 0.62 bpp, respectively. These results confirm that the proposed method effectively reduces storage and transmission requirements while minimizing degradation in visual quality, offering an efficient solution for abstract image compression. Figures 3 to 6 illustrate the perceptual quality of reconstructed images from several test cases using JPEG, SPIHT+DWT, and the proposed method, highlighting differences observable to the human eye.

The results of this study demonstrate that integrating staggered downsampling with block-based DCT provides an effective balance between compression ratio, perceptual quality, and computational efficiency. In comparison with traditional DCT-based methods such as JPEG, the proposed approach achieves higher compression gains while maintaining competitive performance in PSNR, MSSIM, and VIF, confirming that quincunx sampling can eliminate redundant spatial information without substantially compromising visual fidelity.

These findings are consistent with previous research on multi-resolution sampling and perceptual compression, while offering a simpler and more computationally efficient alternative to purely transform-based or neural network–driven approaches. Future work could extend this framework by adapting the downsampling rate according to local variance, integrating perceptual quantization matrices, or incorporating lightweight learning-based refinement modules to further enhance reconstruction quality. Additional studies evaluating the method across diverse datasets, illumination conditions, and image types would strengthen its robustness. Investigations involving color images, multispectral data, and real-time hardware implementation are also important next steps. Overall, this study underscores that a carefully designed hybrid spatial–transform pipeline remains a practical and efficient strategy for image compression, providing a solid foundation for future methodological developments.

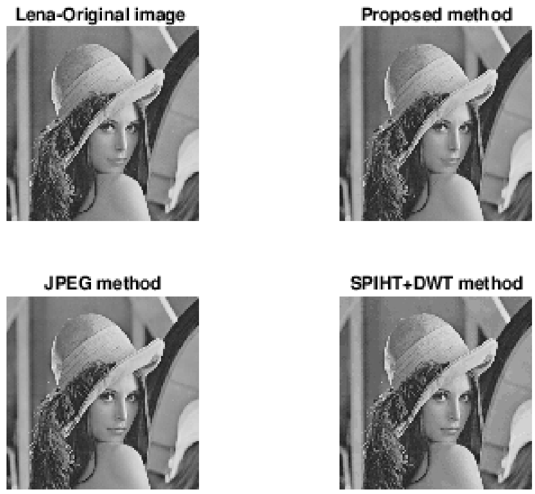

Figure 3. Results - “Lena image”

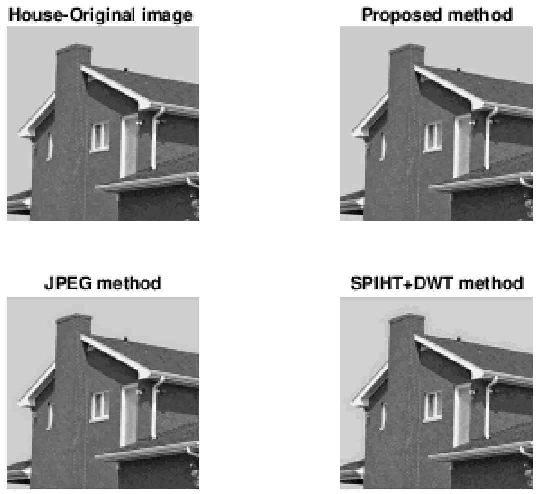

Figure 4. Results - “House image”

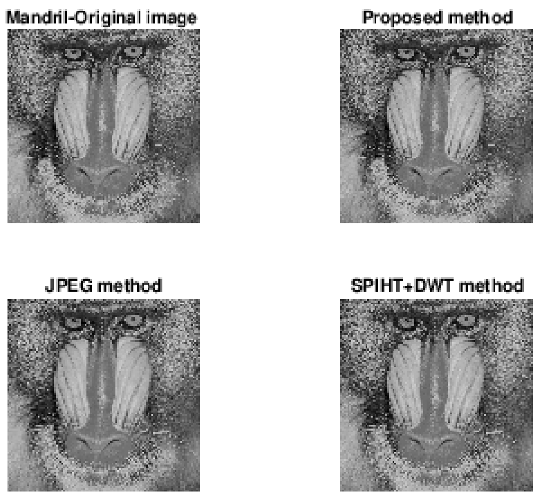

Figure 5. Results - “Mandril image”

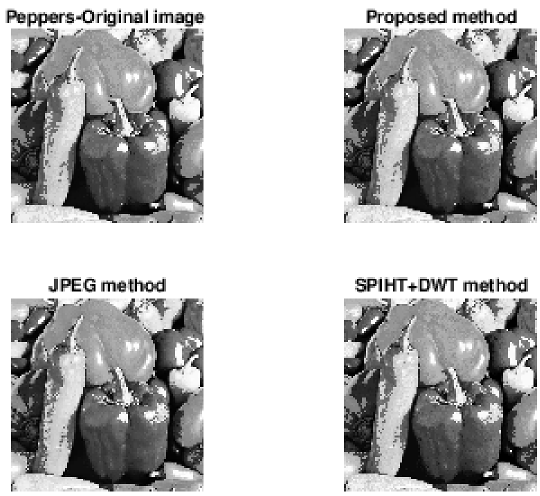

Figure 6. Results - “Peppers image”

4. CONCLUSION

This study introduces a novel hybrid image compression algorithm that integrates downsampling with the DCT. The proposed approach achieves an effective balance between compression efficiency and image quality, outperforming conventional methods such as JPEG and SPIHT+DWT across multiple metrics, including PSNR, SSIM, VIF, bit rate, and compression ratio. Beyond quantitative performance, the method delivers superior visual quality by reducing the blocking artifacts commonly observed in JPEG and by preserving fine textures more effectively than SPIHT+DWT, which tends to obliterate or oversmooth image details. By combining downsampling with selective retention of DCT coefficients, the algorithm attains high compression while maintaining strong perceptual fidelity. This makes it particularly suitable for applications with limited storage or bandwidth, including remote sensing, embedded systems, video compression, and medical image preservation.

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