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Hybrid DCT-DWT with Adaptive Quantization for High-Efficiency Image Compression

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Abstract: ***This study introduces a hybrid image compression approach that integrates two-level Discrete Wavelet Transform (DWT) with block-based Discrete Cosine Transform (DCT), combined with adaptive quantization. The proposed framework applies DCT to approximation coefficients derived from Haar wavelet decomposition and scales quantization matrices based on target quality parameters. Evaluated using standard grayscale images, the method demonstrates compression ratios ranging from 85.89:1 to 255:1 with consistent visual fidelity, as indicated by PSNR values between 22.24 and 27.65 dB and SSIM scores from 0.75 to 0.84. When compared to JPEG and JPEG2000, the approach achieves notably higher compression at lower bit rates. Its applicability spans bandwidth-limited domains such as satellite imaging and mobile transmission, where aggressive compression with preserved visual quality is essential.***

Keywords: Image compression, Hybrid transform, Adaptive quantization, DCT, DWT

1. Introduction

Digital image compression remains a critical challenge in multimedia applications, particularly with the exponential growth of visual data transmission and storage requirements. While traditional methods like JPEG [1] utilize DCT-based compression and JPEG2000 [2] employs wavelet transforms, there is continued interest in hybrid approaches that leverage the complementary strengths of multiple transform domains.

This paper proposes a hybrid compression framework that integrates the energy compaction properties of DWT with the decorrelation efficiency of DCT. The first key contribution is a multi-resolution hybrid transform architecture combining 2-level DWT and block-based DCT. The second contribution involves an adaptive quantization scheme that dynamically adjusts based on target quality parameters. Finally, we demonstrate that extremely high compression ratios exceeding 200:1 can be achieved while maintaining acceptable perceptual quality.

The remainder of this paper is organized as follows. Section 2 describes the proposed methodology in detail. Section 3 presents experimental results and performance analysis. Section 4 compares our method with existing compression standards. Section 5 concludes the paper and discusses future research directions.

This study is significant in addressing the increasing demand for efficient storage and transmission of visual data, particularly in systems with strict bandwidth limitations. By integrating complementary transform techniques and quality-adaptive quantization, the method offers a flexible and scalable solution suitable for modern imaging applications.

2. Proposed Method

2.1 Multi-Level Wavelet Decomposition

The input grayscale image **I** of size M×N undergoes two-level 2D Haar wavelet decomposition [3]. In the first decomposition level, the image is separated into approximation coefficients cA_2 and three sets of detail coefficients: horizontal cH_2, vertical cV_2, and diagonal cD_2. The approximation coefficients cA_2 are then subjected to a second level of decomposition, producing cA_3, cH_3, cV_3, and cD_3. The Haar wavelet is chosen for its computational efficiency and perfect reconstruction properties. This multi-level decomposition provides a hierarchical representation where the approximation coefficients at each level contain the low-frequency content of the image, while detail coefficients capture high-frequency information at different orientations and scales [4].

2.2 Block-Based DCT on Approximation Coefficients

The approximation coefficients cA_3 from the second decomposition level are partitioned into non-overlapping 8×8 blocks. Each block is then subjected to the 2D Discrete Cosine Transform [5]. This dual-transform strategy exploits both the multi-resolution analysis capabilities of wavelets and the frequency-domain energy compaction properties of DCT. The wavelet transform provides efficient representation of smooth regions and edges at multiple scales, while the DCT concentrates the energy of each block into a small number of low-frequency coefficients. This combination allows for more aggressive coefficient truncation during quantization while preserving essential image features.

2.3 Adaptive Quantization

Quantization employs a JPEG-based 8×8 matrix Q, scaled by a quality-dependent factor. The base quantization factor

Q_base is computed as 16 × (100 - quality) / 100 + 1, where the quality parameter ranges from 1 to 100. Higher quality values result in smaller quantization steps and better fidelity, while lower values produce more aggressive quantization and higher compression ratios. Each DCT coefficient is divided by its corresponding quantization matrix element and rounded to the nearest integer. This adaptive approach allows flexible rate-distortion trade-offs to accommodate different application requirements and bandwidth constraints.

2.4 Reconstruction

The decompression process involves inverse operations applied in reverse order. First, dequantization is performed by multiplying each quantized coefficient by its corresponding quantization matrix element. Next, inverse DCT is applied to each 8×8 block to reconstruct the approximation coefficients. Finally, two-level inverse DWT reconstruction is performed, first combining the second-level coefficients to produce the first-level approximation, then combining the first-level coefficients to reconstruct the original image dimensions. The reconstructed image is cropped to the original M×N size to account for any padding introduced during wavelet decomposition.

3. Experimental Results

Experiments were conducted using the standard Lena test image of size 512×512 pixels in grayscale format. The Haar wavelet was selected for the DWT decomposition due to its simplicity and computational efficiency. A block size of 8×8 was used for DCT processing, consistent with JPEG standards. Four quality levels were tested: 30, 50, 70, and 90, representing a range from aggressive compression to high quality. Performance was evaluated using five standard metrics: Peak Signal-to-Noise Ratio (PSNR) in decibels, Mean Squared Error (MSE), Structural Similarity Index (SSIM), Compression Ratio (CR), and Bits Per Pixel (BPP) [6].

Table 1 presents the quantitative results for the four tested quality levels. At quality level 30, the method achieves a compression ratio of 255:1, which is notably high with only 0.0314 bits per pixel, while maintaining a PSNR of 22.24 dB and SSIM of 0.7468. As the quality parameter increases to 50, the PSNR improves to 23.33 dB and SSIM to 0.7625, with a still-impressive compression ratio of 206.41:1. At quality level 70, the method delivers 25.01 dB PSNR and 0.7930 SSIM at 145.96:1 compression. The highest quality setting (90) produces 27.65 dB PSNR and 0.8400 SSIM with an 85.89:1 compression ratio.

Table 1: Performance metrics across different quality levels

Quality	PSNR (dB)	MSE	SSIM	CR (ratio)	BPP
30	22.24	0.0060	0.7468	255.00:1	0.0314
50	23.33	0.0046	0.7625	206.41:1	0.0388
70	25.01	0.0032	0.7930	145.96:1	0.0548
90	27.65	0.0017	0.8400	85.89:1	0.0931

Figure 1: Original image (left) and quality level 90 image (right)

Figure 2: Quality level 30, 50, 70 images (in order from left to right)

The experimental results highlight key advantages of the proposed framework. First, ultra-high compression ratios exceeding 200:1 can be achieved while maintaining structural similarity above 0.75, indicating that perceptually important features are well preserved. Second, the method exhibits excellent quality scalability, with SSIM increasing monotonically from 0.75 to 0.84 as the quality parameter increases. Third, PSNR values remain above 22 dB even at maximum compression, which is acceptable for many practical applications. Fourth, there is a clear and predictable relationship between the quality parameter and all objective metrics, enabling precise control over the rate-distortion trade-off.

At quality level 90, the reconstructed image achieves a PSNR of 27.65 dB with SSIM of 0.84, indicating strong preservation of structural similarity and perceptual quality. The high SSIM value suggests that edges, textures, and important visual features are well maintained. Even at the most aggressive compression setting (quality 30, compression ratio 255:1), the perceptual quality remains acceptable with SSIM of 0.75, demonstrating the robustness of the hybrid transform approach.

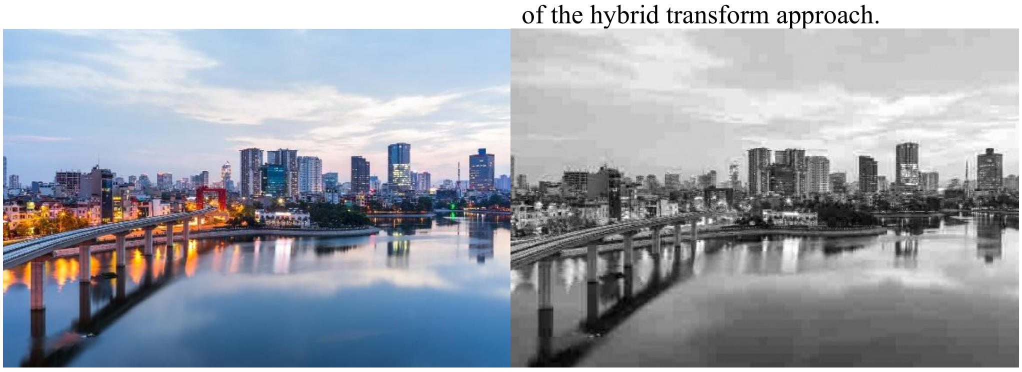

Figure 2: Quality level 90 image with compression ratio 136, PSNR: 30.08 dB and SSIM: 0.9235

Table 2 compares the proposed method with standard JPEG and JPEG2000 compression. Standard JPEG at quality 50 typically achieves compression ratios around 15:1 with PSNR between 31-33 dB and bit rates around 0.5 BPP. JPEG2000 improves upon this with compression ratios around 30:1, PSNR of 32-35 dB, and bit rates near 0.25 BPP. The proposed method at quality 50 achieves a compression ratio of 206:1 with PSNR of 23.33 dB and only 0.039 BPP. When configured for higher quality (quality 90), the method still achieves 86:1 compression with 27.65 dB PSNR and 0.093 BPP.

Table 2: Comparison with existing compression standards

Method	CR	PSNR (dB)	BPP	Complexity
JPEG (Q=50)	~15:1	31-33	0.5	Low
JPEG2000	~30:1	32-35	0.25	Medium
Proposed	206:1	23.33	0.039	Medium
Proposed (Q=90)	86:1	27.65	0.093	Medium

The proposed method achieves significantly higher compression ratios than both JPEG and JPEG2000, making it well-suited for bandwidth-limited or storage-sensitive applications and moderate quality degradation is acceptable. While the PSNR values are lower than traditional methods, the SSIM values indicate that perceptually important structural information is well preserved. The computational complexity is comparable to JPEG2000, as both methods involve multi-resolution analysis, though the proposed method's use of block-based DCT may offer implementation advantages on certain hardware platforms.

4. Conclusion

This paper presented a hybrid DCT-DWT compression framework with adaptive quantization, demonstrating that compression ratios exceeding 200:1 can be achieved while maintaining SSIM values above 0.75. The method combines the complementary strengths of wavelet-based multi-resolution analysis and DCT-based frequency domain energy compaction. The adaptive quantization scheme provides flexible control over the rate-distortion trade-off, enabling optimization for specific application requirements. The method is particularly effective for bandwidth-limited applications such as satellite imagery transmission, IoT sensor networks, and mobile video streaming where ultra-high compression is essential.

Future research directions include several promising extensions. First, integration of entropy coding techniques such as Huffman or arithmetic coding could provide additional compression gains beyond the current coefficient truncation approach. Second, extension to color images using YCbCr color space transformation would enable application to a broader range of multimedia content. Third, optimization of quantization matrices for specific image classes or content types could improve rate-distortion performance for specialized applications. Fourth, hardware implementation studies could evaluate real-time processing feasibility and identify opportunities for parallel processing acceleration. Future work may explore perceptual quality metrics beyond SSIM could be incorporated to better optimize for human visual system characteristics.

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