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Efficient Image Compression Techniques: A Study On Vector Quantization, LZW, And Lossy Compression

Amrutbhai N. Patel
Associate Professor, Faculty of Engineering and Technology, Ganpat University

Samir B. Joshi
Assistant Professor, Faculty of Engineering and Technology, Ganpat University

A. J. Patel
Professor, LDRP-KSV University, Gandhinagar,

Abstract

This paper presents a comprehensive study on efficient image compression techniques, focusing specifically on vector quantization (VQ), Lempel-Ziv-Welch (LZW) algorithm, and lossy compression methods. Image compression plays a crucial role in reducing the storage space required for digital images while maintaining acceptable visual quality. Vector quantization is a popular technique that achieves compression by representing image blocks with reduced number of representative vectors. The LZW algorithm, known for simplicity and effectiveness, is explored for its application in image data compression. The paper discusses the principles, advantages, and limitations of each technique, along with experimental results showcasing their performance in terms of compression ratios (CR), Peak Signal to Noise Ratio (PSNR), Mean Square Error (MSE) and Structural Similarity Index Measurement (SSIM) for image quality preservation. The comparative analysis provides insights into the strengths and weaknesses of these methods, aiding in the selection of suitable compression approaches for image processing applications.

Keywords: Discrete wavelet transform(DWT), Lossy Image Compression, Mean square error(MSE), Peak signal to noise ratio(PSNR), Structural similarity index measurement(SSIM), Vector quantization (VQ).

1. Introduction:

Image compression is a fundamental process in digital image processing that involves reducing the size of an image file while preserving its visual quality to the extent possible. (Patel et al., 2014) the primary goal of image compression is to minimize the storage space required to store digital images and facilitate efficient transmission over networks or storage on devices with limited resources.

The need for image compression arises due to the large amounts of data inherent in high-resolution images captured by modern digital cameras and generated by various imaging systems. Storing and transmitting such data without compression can be impractical and resource-intensive. (Patel et al., 2014) image compression techniques aim to overcome these challenges by exploiting redundancies and removing unnecessary

Corresponding author. Tel.: 9879831765
E-mail address:amrut.patel@ganpatuniversity.ac.in

information from images.

Image compression methods can generally be divided into two main types: lossless compression and lossy compression. Lossless compression algorithms preserve the integrity of the original image data, ensuring that no information is lost during the compression and decompression processes. These methods are suitable for scenarios where preserving the original image quality is crucial, such as medical imaging or graphic design. Notable examples of lossless compression algorithms include Run-Length Encoding (RLE), which efficiently encodes consecutive identical pixel values, Huffman coding, which assigns shorter codes to more frequent data values, and the Lempel-Ziv-Welch (LZW) algorithm, which replaces recurring patterns with codes to achieve compression.

Conversely, lossy compression methods attain greater compression ratios by sacrificing less perceptible image details to the human eye. These techniques are well-suited for scenarios where storage or bandwidth limitations are paramount, such as multimedia streaming, web graphics, and mobile photography. Common lossy compression algorithms encompass the Discrete Cosine Transform (DCT) utilized in JPEG compression, Wavelet Transform employed in JPEG 2000, and Vector Quantization (VQ).

The choice between lossless and lossy compression depends on factors such as the desired compression ratio, the importance of preserving image quality, and the specific application requirements. Both types of compression techniques have their advantages and limitations, and researchers continually explore and develop new algorithms and approaches to improve compression efficiency and image quality.

In this context, this paper aims to provide a detailed exploration of efficient image compression techniques, focusing on vector quantization (VQ), Lempel-Ziv-Welch (LZW) algorithm, and lossy compression methods. The study includes an analysis of the principles, advantages, and limitations of these techniques, along with experimental results demonstrating their performance in terms of compression ratios and image quality preservation. The findings will contribute to a better understanding of image compression and aid in selecting appropriate techniques for various image processing applications.

2. Proposed Approach:

The proposed methods present a Lossy image compression algorithm that incorporates wavelet transform, Global Thresholding, Vector quantization, and Source coding techniques like Huffman coding and LZW coding. This innovative Lossy image compression technique is designed for digital image areas that demand a higher compression ratio while maintaining superior image reconstruction quality, such as in criminal investigations and medical imaging applications.

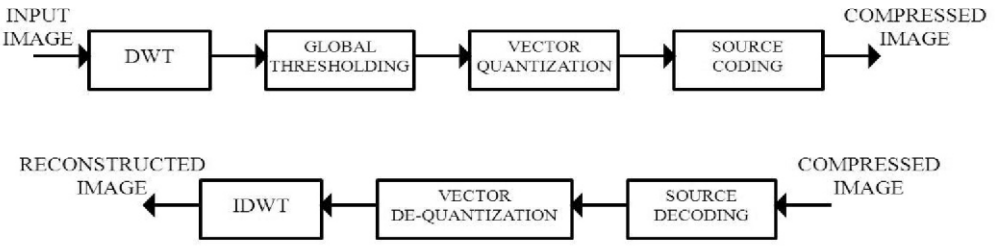


Figure 1: Block diagram of Proposed Work

The description of the proposed work is illustrated in Figure1. Initially, the input image undergoes the discrete wavelet transform (DWT), which breaks down the image into a series of wavelet coefficients. The wavelet transform reduces inter-pixel redundancy, leading to increased image compression capabilities. (Meng et al., 2010)

The discrete wavelet transform (DWT) starts by passing the input image through an analysis filter bank containing low and high pass filters. At each decomposition level, the low pass filter extracts coarse averaged information, while the high pass filter extracts detailed differences. After filtering, the outputs are down sampled by a factor of two. Image compression using DWT involves two separate 1D transforms along the rows and columns. First, the input image is low and high pass filtered along the rows, then down sampled by 2, creating low and high frequency row images. These row images are then filtered along the columns and down sampled by 2, generating four sub band images: FLL, FLH, FHL, and FHH. DWT reduces redundancy between pixels in a reversible way. The optimal wavelet filter is chosen based on evaluating compression ratio, PSNR, and SSIM for various wavelet filters and orders. Compared to DCT and Fourier transforms, DWT provides better energy compaction, representing most energy in fewer coefficients for higher compression ratios.

Thresholding and vector quantization are techniques used to reduce psycho-visual redundancy in order to achieve higher image compression. Typically, images contain numerous wavelet coefficients that are close to or equal to zero. Global thresholding is a method employed to modify these coefficients, creating long sequences of zeros within the wavelet coefficient sequence. In global thresholding, coefficients with absolute values below a chosen threshold are set to zero, while coefficients above the threshold are retained. The primary objective of global thresholding is to introduce a significant number of zeros while preserving a substantial amount of detail compared to other thresholding methods. It involves transforming wavelet coefficients into another sequence and is an irreversible process.

After thresholding, the resulting coefficients undergo quantization through the vector quantization technique. Vector Quantization (VQ) stands out as a robust method for compressing digital images. (Kalaivani et al., 2013) It is a classical approach for Lossy image compression, effectively reducing psycho-visual redundancies. Unlike scalar quantization, which applies quantization directly to the original image without segmentation, vector quantization partitions the data into vectors, leading to a higher compression ratio albeit at the cost of reversibility.

Vector quantization (VQ) is a signal processing technique used for data compression. (Thepade et al., 2015) It is especially useful for compressing high-dimensional data vectors, such as those encountered in speech, image, and video coding applications. The main idea behind vector quantization is to represent a large set of input vectors by a smaller set of representative vectors, called code-vectors or code-words, from a predefined codebook. (Thepade et al., 2015)

An input image of MxM pixels, where M is a power of 2, is split into CxD blocks, with dimensions that are also powers of 2. Vector quantization (VQ) then creates N training vectors, where N = (MxM)/(CxD). A codebook size n, another power of 2, is set. P is calculated as P = N/n, and every Pth training vector becomes a code vector until reaching the desired n codebook size. After VQ, the discrete quantized values undergo source encoding via Huffman or LZW coding. This maps the vector-quantized coefficients to symbols, reducing bits per symbol by considering their probabilities. Either Huffman or LZW encoding reduces redundancy compared to the methods used in other research paper. (Nandi et al., 2012)

For decompression, the compressed image undergoes source decoding (Huffman/LZW) followed by vector de-quantization, which is irreversible causing some loss. The de-quantized coefficients then go through the inverse discrete wavelet transform (DWT) to reconstruct the spatial domain input image. Unlike de-quantization, the DWT is reversible without information loss.

3 Performance Parameter:

Finally, the performance of this proposed work is assessed according to the following evaluation parameters.

a. **Compression ratio (CR):** When comparing different image compression techniques, the compression ratio is one of the key metrics used to assess their performance. A technique that consistently achieves higher compression ratios while maintaining satisfactory image quality is considered more effective and efficient in terms of compression.

b. **Mean Square Error (MSE):** The Mean Squared Error (MSE) quantifies the average of the squared intensity differences between pixels in two images. It serves as a standard metric for assessing the dissimilarity between an original image and its reconstructed or compressed counterpart. MSE finds extensive application in image processing and compression algorithms, enabling an objective evaluation of the reconstructed image's quality relative to the original.

c. **Peak Signal to Noise Ratio (PSNR):** PSNR is a more interpretable metric compared to MSE, as it provides a logarithmic scale that correlates well with human perception of image quality. Higher PSNR values indicate better image quality, while lower PSNR values suggest lower quality or higher distortion in the reconstructed image compared to the original

d. **Structural Similarity Index Measurement (SSIM):** SSIM stands for Structural Similarity Index Measure, and it is a widely used metric in image processing and compression to evaluate the similarity between two images, typically the original image and a reconstructed or compressed version of the same image. (Wang et al., 2004) SSIM is designed to assess not only pixel-wise differences but also structural and perceptual similarities, making it a more comprehensive metric for image quality assessment compared to simple pixel-based measures like MSE (Mean Squared Error). SSIM value is 1 in the case of two identical sets of original image and reconstructed image. (Zhang et al., 2011)

4. Results and discussion:

This paper presents the outcomes of our proposed approach using vector quantization, focusing on evaluating the test images CAMERAMAN (256 x 256) and BARBARA (256 x 256) with LZW coding. The results are detailed in Table1 including parameters such as PSNR, CR, RMSE, and SSIM. These metrics are examined across various cluster sizes and codebook configurations in Vector Quantization.

Table 1: MSE, PSNR, CR and SSIM for various decomposition level, and wavelet families using wavelet transform and LZW Coding

Wavelet	Decomposition level (BARBARA IMAGE) 1				3			
	MSE	PSNR (db)	CR (%)	SSIM	MSE	PSNR (db)	CR (%)	SSIM
HAAR	601.8	20.3	66.1	0.90	931.8	18.4	86.4	0.80
DB4	576.3	20.5	64.5	0.90	756.4	19.3	84.0	0.84
SYM4	556.8	20.7	64.4	0.90	737.1	19.5	84.0	0.85
Rbio6.8	563.6	20.6	61.4	0.90	743.0	19.4	81.0	0.85
DMEY	542.5	20.8	34.3	0.91	768.8	19.3	36.0	0.85

Table 1 displays the performance metrics, including PSNR, MSE, CR, and SSIM, for image compression utilizing the BARBARA image (256x256) with Wavelet Transform and Huffman Coding. From this table it is observed that MSE and CR increases, while PSNR and SSIM decrease as decomposition level increases. Table1 shows the DMEY wavelet gives lowest CR of 34.27 for decomposition level-1 and HAAR give Highest CR of 86.36 for decomposition level-3. HAAR Wavelet gives lowest SSIM of 0.8035, while DMEY gives highest SSIM of 0.9053 and DMEY Wavelet gives highest PSNR of 20.78, whereas HAAR gives lowest PSNR of 18.43.

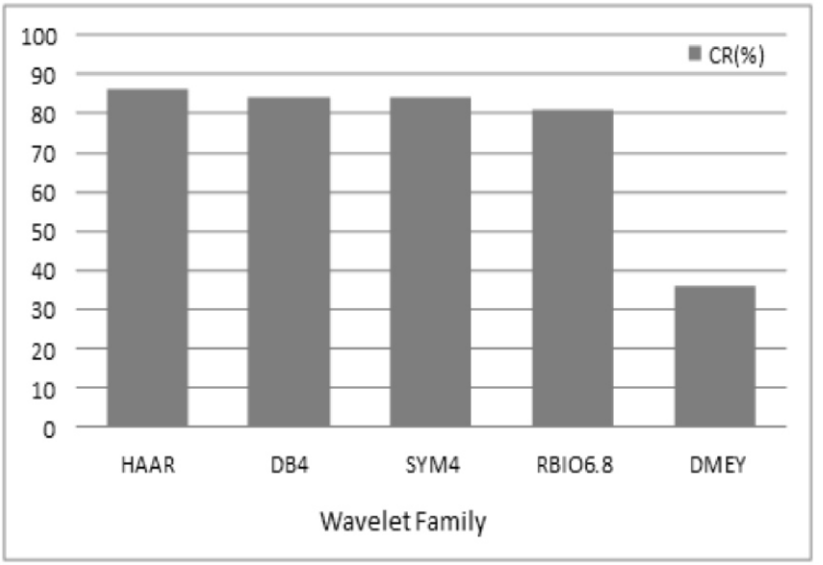


Figure 2: CR for various wavelets and decomposition level-3 for BARBARA

Figure 2 represents the performance evaluation of image compression using CR for BARBARA image. The results were achieved through the application of wavelet transform and Huffman coding techniques. Based on these findings, it is concluded that HAAR wavelet yields the best outcomes, while DMEY wavelet performs poorly in terms of compression ratio (CR).

Table 2: Result comparison of cluster size (4x4) and cluster size (8x8) using MSE, PSNR, CR and SSIM for BARBARA image

Parameter	Cluster size (4x4) Codebook size					Cluster size (8x8) Codebook size				
	16	32	64	128	256	16	32	64	128	256
MSE	448	331	305	247	185	724	556	459	328	194
PSNR(db)	22	22	23	24	25	20	21	22	23	25
CR (%)	99	98	96	91	83	93	92	84	68	37
SSIM	0.89	0.90	0.92	0.94	0.95	0.81	0.8	0.88	0.92	0.95

Table 2 depicts a performance comparison between cluster sizes of 4x4 and 8x8 using metrics such as MSE, PSNR, CR, and SSIM for the BARBARA image. These tables were generated by employing various codebook sizes in vector quantization and employing LZW coding techniques. The analysis indicates that there is variation in parameters with changes in both the codebook size and cluster size. Specifically, as the codebook size increases, the compression ratio (CR) decreases, while PSNR and SSIM increase.

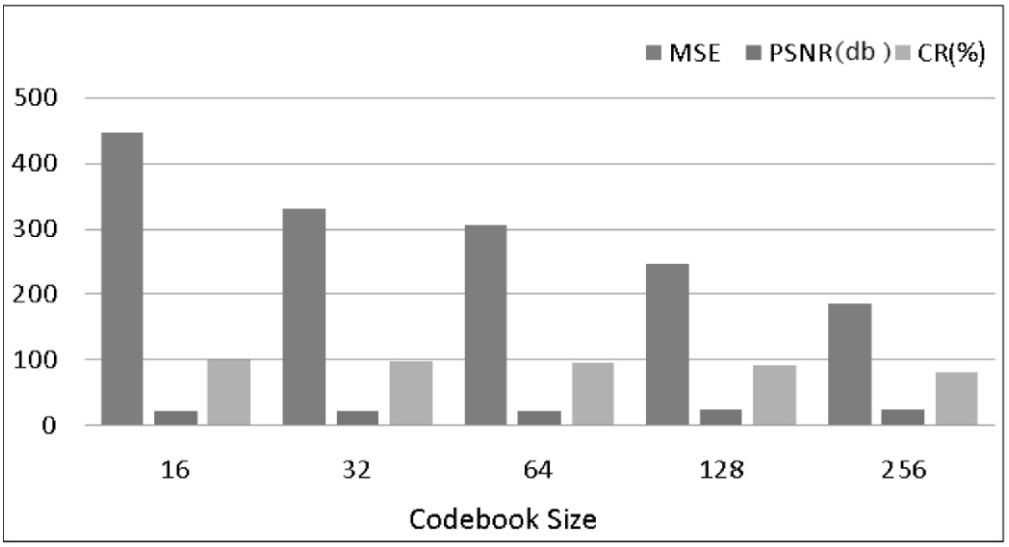


Figure 3: MSE, CR and PSNR using various codebook size and cluster size (4x4) for BARBARA image.

Figure 3 illustrates the performance assessment of MSE, PSNR, and CR using a cluster size of 4x4 for the BARBARA image. These results were obtained by employing different codebook sizes and the 4x4 cluster size in vector quantization and LZW coding techniques. The analysis reveals that as the codebook size increases, the compression ratio (CR) typically decreases, while the quality of the reconstructed image improves with higher PSNR and SSIM values.

Table 4: Comparisons of proposed work with reference paper using CR and PSNR for CAMERAMAN image

Work	(Shenyang et al., 2010)	(Sudhakar et al., 2007)	(Joshi et al., 2008)	(Kalaivani et al., 2013)	Proposed work
PSNR(db)	10	13.03	7.49	13.42	31.59
CR	30.87	26.81	27.1	27.31	47.17

Table 4 displays a comparison between our proposed method and a reference paper using CR and PSNR metrics for the CAMERAMAN image. Our proposed approach relies on Vector Quantization and LZW coding techniques. The table reveals that our method outperforms the existing works mentioned in the reference paper, showcasing better performance in terms of PSNR and CR.

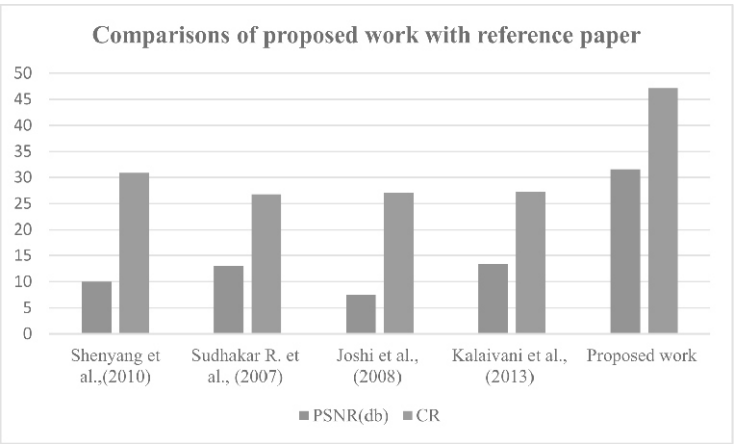


Figure 4: comparisons of proposed work with reference paper using CR and PSNR for CAMERAMAN image

Figure 4 displays a comparison between our proposed method and a reference paper using CR and PSNR metrics for the CAMERAMAN Image. Our approach relies on Vector Quantization and LZW coding techniques. The results indicate that our method outperforms the existing works by Sanchez, Sudhakar, Joshi, and K. Kalaivani in terms of both PSNR and CR.

5. Conclusion:

The proposed work involves measuring various parameters such as compression ratio, PSNR, MSE, and SSIM, followed by a comparison with existing methods. The focus is on developing a simulation that implements algorithms for the lossy compression of two-dimensional images. While this simulation generally performs reasonably well, there are some components that exhibit suboptimal performance. For instance, increasing the cluster size in Vector Quantization can enhance compression performance but at the cost of image quality degradation. Overall, the proposed approach significantly improves the image compression process by drastically increasing the compression ratio, albeit with a slight reduction in PSNR, which aligns with the method's goal of delivering high-quality images in areas requiring such fidelity. SSIM emerges as a superior parameter compared to MSE for assessing reconstructed image quality. Combining Vector Quantization (VQ) with LZW coding in the proposed method yields better quality and higher compression ratios compared to existing techniques.

6. Future Work:

The evolving landscape of lossy Image Compression encompasses an emerging standard that integrates numerous research contributions in vector quantization, promising significant advancements in image compression for the foreseeable future. Future endeavours aim to enhance the wavelet-based vector quantization algorithm, ensuring optimal performance across various image formats. This entails implementing an efficient codebook and a wavelet-based tree structure to further reduce computational complexity. Moreover, improvements in the compression algorithm can be achieved through the analysis of wavelet-based vector quantization, leveraging image de-noising and compressive sensing techniques.

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