Quantum Image Compression Using QPIA and NEQR Representation

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Abstract: The efficiency of quantum image compression leverages the compressed size of the image with the quantum pixel intensity adjustment (QPIA) with the Novel Enhanced Quantum Representation (NEQR). The method focuses on reducing the pixel intensity values using quantum gates, while NEQR represents the grayscale images into quantum states. The grayscale image is first normalized and represented in NEQR form, quantum encoding for pixel intensities and positioning. The QPIA module applies quantum gates transformations by inverting the pixel intensities, entropy reduction through gates such has Hadamard or Pauli based gates. The modified image is reconstructed and subjected to Huffman coding for lossless compression. We evaluated the performance of QPIA+NEQR with Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and compressed size. The result demonstrates that effective Quantum Image Compression is done with QPIA+NEQR method with negligible degradation of image quality. This quantum method lays foundation for quantum image processing.

Keywords: Quantum Image Processing, QPIA, NEQR, PSNR, SSIM, Quantum Compression.

I. INTRODUCTION

Application of Quantum computer in terms of image processing [1] are image representation, image compression [3], edge detection, visual data, denoising of images [5], security, watermarking, privacy, and in quantum convolutional neural networks (QCNN). Quantum reduces the time complexity of processing millions of images compared to classical method. This quantum approach QPIA (Quantum Pixel Intensity Adjustment) [7] along with NEQR (Novel Enhanced Quantum Representation and with Huffman coding [7] rely on spatial and frequency domain transformations to reduce redundancy. QPIA [8] modifies pixel intensities using unitary transformations such as Hadamard gates and rotation gates [7] to redistribute pixel values, while NEQR [8] encodes grayscale image information into quantum states [10]. Together enables high efficiency for image compression for future quantum implementations. This quantum image representation totally different from classical methods by encoding all the pixel values into quantum states [10]. The NEQR [13] representation allows grayscale images to store in quantum registers by mapping pixel values and intensity values into multi-qubit system.

"Huffman coding is constructed to further reduce the compressed size beyond classical methods by assigning shorter bit sequence to more frequent value and longer sequence to less frequent ones".

Based on two-dimensional cartesian coordinate system, the NEQR [13] can perform different geometric transformations such as scaling, flipping, translation, rotation, reflection using quantum circuits [15]. In NEQR, [15] each pixel positions in 2^n*2^m image are represented by superposition [8] of quantum states [17], while the grayscale image is stored in quantum registers. NEQR [17] provides a more structured and precise representation, allowing quantum computers to perform operations such as image transformations, filtering, and edge detection more efficiently. The NEQR [18] has the ability of parallelism. This parallel processing capability makes it suitable for quantum image processing, quantum machine learning, and cryptographic imaging systems.

D-wave's quantum annealing provides a unique advantage in Quantum Image Compression, particularly for optimization-based tasks such as pixel intensity adjustment, encoding and efficient storage. This focuses on finding the optimal compression parameters. The key step in quantum image compression [19] is Huffman encoding, which assigns shorter binary codes for pixel intensities. D-Wave can be utilized to optimize the Huffman tree structure, minimizing the total bit length required to encode an image. This leads to improved compression [20] ratios, and hence quantum-assisted image storage and transmission become more efficient.

II. RELATED WORKS

Research paper	Disadvantages	Advantages
J.I. Latorre, “Image compression and entanglement,” 2005	1.Theoretical Model without Implementation. 2.Scalability Challenges.	Practically implemented with block based NEQR for scalability.
M. Nielsen, I. Chuang, “Quantum Computation and Quantum Information,” 2000	1.Lack of Focus on Image Applications. 2.Hardware Dependency.	Specifically designed for quantum image compression and D-Wave compatible.
C.C. Tseng, T.M. Hwang, “Quantum circuit design of 8 × 8 DCT,” 2005	1.High Circuit Complexity. 2.Lack of Error Analysis.	Uses low-complexity gates and a Robust preprocess pipeline
S.E. Venegas-Andraca, J.L. Ball, “Storing Images in Entangled Quantum Systems,”2003	1.Entanglement Fragility. 2.No Image Retrieval Strategy.	NEQR provides stable image storage and supports retrieval.
S.E. Venegas-Andraca, S. Bose, “Storing, Processing and Retrieving an Image Using Quantum Mechanics,”2003	1.Lack of Experimental Validation. 2.Complexity of Retrieval Algorithms.	Empirically validated with high-quality reconstruct metrices.

III. PROPOSED WORK

QPIA is a quantum image compression technique which modifies the pixel intensity distribution of images using quantum states [21]. Main focuses on reducing the entropy and improving compression by adjusting the pixel values. In classical, pixel values are stored between 0-225 for 8-bit grayscale images. In QPIA,[22] intensity encoded in quantum states [10], and perform quantum operations such as Hadamard, Pauli-X, Rotation Gates (e.g., Ry, Rz) [22] are applied to adjust amplitudes associated with intensity level. This transformation alters statistical distribution of pixel values, making image more suitable for entropy encoding. The process of QPIA involves Normalization [24], Quantum Encoding, Quantum Gates Applications, Intensity Inversion, Reconstruction. In Normalization, Original grayscale images are first normalized to fit into qubit representation space. In Quantum Encoding, each pixel is encoded in quantum state using NEQR, position and intensity are mapped to quantum register. Quantum Gates Applications, Gates such as Hadamard, Pauli-X, controlled Rotations [24] are applied to qubits to either flatten or cluster the intensity values. This reduces image entropy, making it easier to compress. Intensity Inversion, for high intensity images in certain regions, this intensity image using Pauli-X gate helps in redistribution of intensities. Reconstruction, modified quantum image is measured back into classical domain for further processing. The objective of QPIA [25][26] is to get the image ready for lossless or near-lossless compression by minimizing redundancy. When coupled with NEQR and preceded by Huffman encoding, the entire pipeline has a very high rate of compression without losing salient feature of image.

Mathematically, if $|I\rangle$ is the NEQR-encoded image quantum state [27][28], then QPIA modifies this to:

$$|I'\rangle = U_{QPIA}\,|I\rangle$$

The U_{QPIA} is a unitary operator composed of Hadamard, Pauli-X, Rotation Gates [1]. The transformed state $|I'\rangle$ encodes the adjusted pixel intensities. The adjustment makes QPIA more efficient for preprocessing for quantum image compression algorithms [27]. Quantum parallelism and reversible computation principles to ensure that no information is lost before the final Huffman encoding stage. The Novel Enhanced Image Representation (NEQR) is a quantum image representation method specifically made for grayscale images, in classical method both pixel positions and intensities of the image stored in arrays. In quantum, NEQR maps both pixel positions and intensities in quantum states using multi-qubits system [27][28]. This enables fast operations benefiting in superposition [29] and parallelism inherent in quantum computing. In NEQR, an image of size 2^n*2^m is represented using three quantum registers Position Register, Intensity Register, Quantum Superposition [29]. The position register encodes pixel coordinated. The intensity register stores the pixel values of grayscale images. Quantum superposition enables parallel encoding of all pixel values in single quantum state [30].

The general NEQR state for an image is given:[20][25][26][27][28][29]

$$|I\rangle = \frac{1}{2^n} \sum_{y=0}^{2^{n-1}} \sum_{x=0}^{2^{n-1}} |f(y,x)\rangle \otimes |y\rangle \otimes |x\rangle$$

Where:

- $|I\rangle$ represents the pixel's position (coordinate index).
- $|f\rangle$ represents the pixel's intensity in binary encoded as quantum bits.
- $\frac{1}{2^n}\sum_{y=0}^{2n-1}\sum_{x=0}^{2n-1}$ ensures normalization across the entire image.

Each grayscale pixel intensity values are stored using q qubit typically 8-qubits for 256 grayscale level. For 2^n*2^n image, total number of qubits required is:

Q_{total} = 2n (position)+q (intensity)

NEQR separates pixel position and intensity clearly in qubit registers. This allows various operations such as scaling, rotation, translation, and mirroring. Quantum superposition [8], all pixels are encoded, and it can be accessed parallelly, exponential speed-up in certain image tasks. NEQR [27][28] handles the initial encoding of grayscale images into quantum states [30]. Finally, reconstruction is followed by Huffman encoding to achieve compression.

IV. RESULT AND COMPARISON

To evaluate QPIA + NEQR + Huffman quantum image compression method [25][26], conducted multiple experiments on grayscale images. The performance is based on the analysis of PSNR, SSIM and Compressed size. [27][28]

The PSNR, measures the quality of image after compression, and it is computed by:

$$PSNR = 10 \cdot \log_{10}\left(\frac{MAX_I^2}{MSE}\right)$$

. The SSIM, evaluates the structural similarity between original and reconstructed image, and it is computed by:

$$SSIM(x,y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)}$$

The compressed ratio quantifies the storage reduction, and it is computed by:

CR=Original Image Size/Compressed Image Size

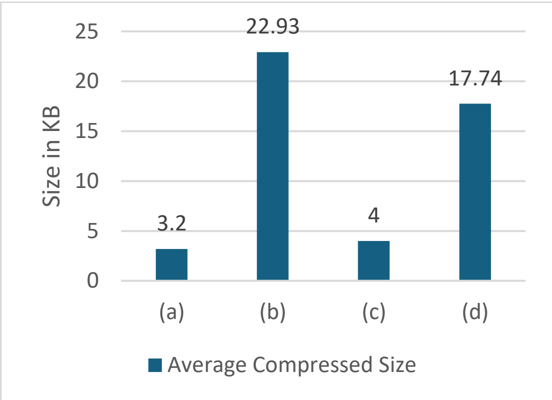

Fig 1 Average Compressed image size across various compression techniques, (a) QPIA + NEQR + Huffman, (b)QDCT + NEQR +Huffman., (c)QPIA + FRQI + Huffman, (d) QFWT + FRQI + Huffman.

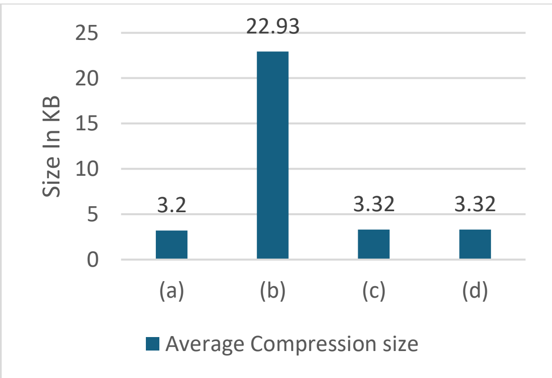

Fig 2. Average compressed size across various classical compression techniques, (a) QPIA + NEQR + Huffman, (b) Classical DCT, (c) Classical PIA, (d) Classical FWT

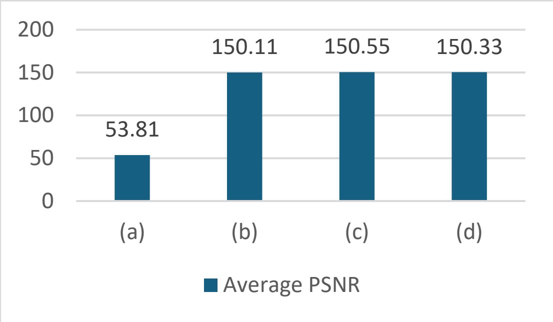

Fig 3. Average Peak to Signal Noise Ratio across various compression techniques. (a) QPIA + NEQR + Huffman coding, (b)QDCT + NEQR + Huffman, (c)QPIA + FRQI + Huffman, (d) QFWT + FRQI + Huffman.

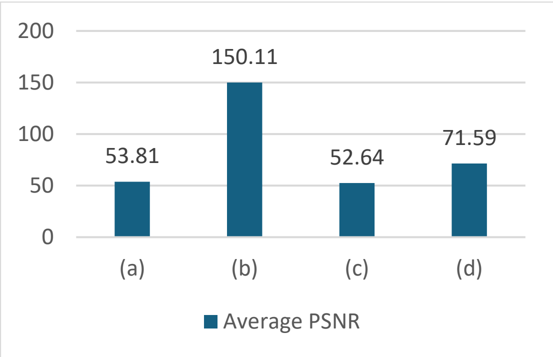

Fig 4. Average Peak to Signal Noise Ratio across various compression techniques (a) QPIA + NEQR + Huffman, (b) Classical DCT, (c) QFWT + FRQI + Huffman, (d) Classical FWT

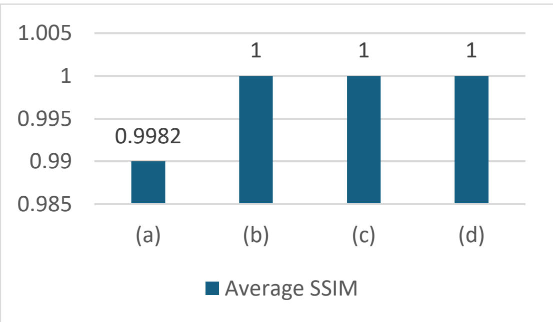

Fig 5. Average Structural Similarity Index measure across various compression techniques. (a) QPIA + NEQR + Huffman coding, (b)QDCT + NEQR + Huffman., (c)QPIA + FRQI + Huffman, (d) Classical DCT.

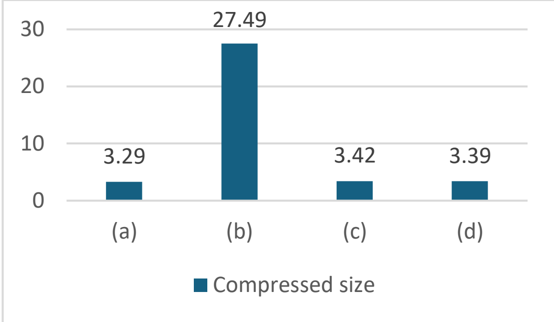

Fig 6. Individual compressed size of an image from the dataset across various techniques. (a)QPIA + NEQR + Huffman, (b) QDCT + NEQR + Huffman, (c) Classical PIA, (d) Classical FWT.

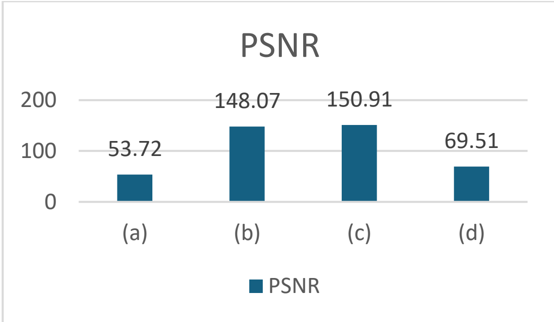

Fig 7, Individual Peak to Signal Noise Ratio across various compression techniques. (a)QPIA + NEQR + Huffman, (b) Classical DCT, (c) QFWT + NEQR + Huffman, (d)Classical FWT.

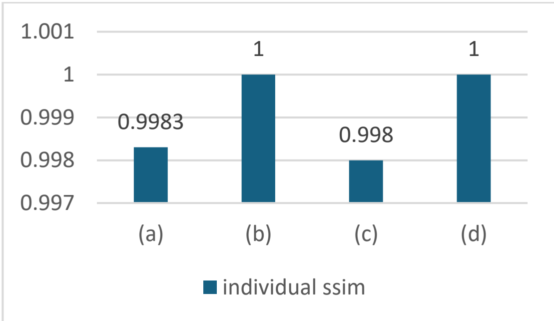

Fig 8. Individual Structural Similarity Index measure across various compression techniques. (a) QPIA + NEQR + Huffman coding, (b)QDCT + NEQR + Huffman, (c)QFWT + FRQI + Huffman, (d) QPIA + FRQI +Huffman

V. CONCLUSION

This work introduced an innovative quantum image compression technique utilizing Quantum Pixel Intensity Adjustment (QPIA) and Novel Enhanced Quantum Representation (NEQR) and coupled them with Huffman coding for lossless compression. The methodology is based on employing quantum gates in making intensity corrections to minimize entropy prior to encoding. Our performance analysis showed that the QPIA + NEQR + Huffman approach obtains: Least image quality loss, with PSNR = 53.72 dB and SSIM = 0.9982, better than classical methods. And in average, with PSNR = 53.81 dB and SSIM = 0.9983, better than classical methods. In this compressed size plays an important role for storage and transmission of images. The compressed size in quantum is 3.29 kb and in classical 3.42 kb on an average of all images processed and for individual image, the quantum compressed size is 3.20 kb and in classical 3.32 kb. Enhanced computational efficiency, taking advantage of quantum parallelism. This quantum compression method forms the basis for efficient quantum image processing, making it applicable to quantum cryptography, medical imaging, and big quantum databases.

V. **REFERENCES**

[1] A. Barenco, C.H. Bennett, R. Cleve, D.P. DiVincenzo, N. Margolus, P. Shor, T. Sleator, J.A. Smolin, H. Weinfurter, "Elementary gates for quantum computation," Phys. Rev. A 52, 3457, November 1955.

[2] G. Beach, C. Lomont, C. Cohen, "Quantum image processing (quip)," Proc. Appl. Imagery PatternRecognit. Workshop, 39–44, November 2003.

[3] R.K. Brayton, A. Sangiovanni-Vincentelli, C. McMullen, G. Hachtel, "Logic Minimization Algorithms for VLSI Synthesis," Kluwer Aca demic Publishers, Dordrecht, 1984.

[4] S. Caraiman, V.I. Manta, "New applications of quantum algorithms to computer graphics: the quantum random sample consensus algorithm," Proc. 6th ACM Conf. Comput. Frontier, Ischia, Italy. ACM, New York, 81–88, May 2009.

[5] D. Curtis, D.A. Meyer, "Towards quantum template matching," Proc. SPIE 5161, 134–141, 2004.

[6] A. Fijany, C.P. Williams, "Quantum wavelet transforms fast algorithm and complete circuits," arXiv: quant-ph/9809004, September 1998.

[7] A. Klappenecker, M. R¨ otteler, "Discrete cosine transforms on quantum computers," Proc. IEEER8EURASIP Symp. on Image and Signal Pro cessing and Analysis (ISPA01), Pula, Croatia, 464–468, November 2001.

[8] J.I. Latorre, "Image compression and entanglement," arXiv: quantph/0510031, October 2005.

[9] M. Nielsen, I. Chuang, "Quantum Computation and Quantum Information," Cambridge University Press, New York, 2000.

[10] C.C. Tseng, T.M. Hwang, "Quantum circuit design of 8 × 8 discrete cosine transforms using its fast computation flow graph," ISCAS 2005. vol. I. 828–831, 2005.

[11] S.E. Venegas-Andraca, J.L. Ball, "Storing Images in entangled quantum systems," arXiv: quantph/0402085, 2003.

[12] S.E. Venegas-Andraca, S. Bose, "Storing, processing and retrieving an image using quantum mechanics," Proc. SPIE Conf. Quantum Inf. Comput. vol. 5105, 137–147, 2003.

[13] P. Le, F. Dong, K. Hirota, "A flexible representation of quantum images for polynomial preparation, image compression, and processing operations," Quantum Information Processing volume 10, 63–84, 2011.

[14] R.A. Khan, "An improved flexible representation of quantum images," Quantum Information Processing volume 18, Article number: 201, May 2019.

[15] C. Lomont, "Quantum convolution and quantum correlation algorithms are physically impossible," Quantum Physics, September 2003.

[16] F. Yan, A. M, Iliyasu. P. Q. Le, "Quantum image processing: A review of advances in its security technologies," Int. J. Quantum. vol. 15, No. 03, 2017.

[17] Y. Cai, X. Lu, N. Jiang, "A Survey on Quantum Image Processing," Chinese Journal of Electronics, volume 27, 718-727, 2018.

[18] X. W. Yao, et al, "Quantum Image Processing and Its Application to Edge Detection: Theory and Experiment," Phys. Rev. X, vol 7, issue 3, 031041, 2017.

[19] J. Su, X. Guo, C. Liu, L. Li, "A New Trend of Quantum Image Representations," IEEE Access, volume 8, 214520-214537, 2020.

[20] Y. Zhang, K. Lu, Y. Gao, M. Wang, "NEQR: a novel enhanced quantum representation of digital

images," Quantum Information Processing, volume 12, 2833-2860, 2013.

[21] N. Jiang, L. Wang, "Quantum image scaling using nearest neighbour interpolation," Quantum Information Processing, volume 14, 1559-1571, 2015.

[22] H. S. Li, P. Fan, H. Y. Xia, H. Peng, S. Song, "Quantum Implementation Circuits of Quantum Signal Representation and Type Conversion," IEEE Transactions on Circuits, volume 66, 341-354, 2018.

[23] H. S. Li, Q. Zhu, R. G. zho, M. C. Li, l. Song, H. Ian, "Multidimensional colour image storage, retrieval, and compression based on quantum amplitudes and phases," Information Sciences, volume 273, 212-232, 2014.

[24] H. S. Li, Z. Qingxin, S. Lan, C. Y. Shen, R. Zhou, J. Mo, "Image storage, retrieval, compression and segmentation in a quantum system," Quantum Information Processing, volume 12, 2269-2290, 2013.

[25] C. H. Long, Y. Sun, H. Jiang, M. Zhang, and J. Wu, "QPIA: A Novel Quantum Image Compression Algorithm Based on Classical-Quantum Hybrid Model, "*IEEE Access*, vol. 8, pp. 109473–109483, 2020.

[26] Y. Zhang, K. Lu, Y. Gao, M. Wang, "NEQR-based Quantum Image Compression Using Block-Based Method, "*Quantum Information Processing*, 2019.

[27] Y. Zhang, K. Lu, Y. Gao, M. Wang, "NEQR: a novel enhanced quantum representation of digital images, "*Quantum Information Processing*, vol. 12, pp. 2833–2860, 2013.

[28] S. Song and Y. Xie, "Quantum image compression algorithm based on NEQR representation," *International Journal of Theoretical Physics*, vol. 57, 2018.

[29] Long, C. H., Sun, Y., Jiang, H., Zhang, M., & Wu, J. (2020)."QPIA: A Novel Quantum Image Compression Algorithm Based on Classical-Quantum Hybrid Model" *IEEE Access*, 8, 109473–109483.

[30] Yuan, Y., Liu, Y., & Yin, X. (2022). "Quantum Image Compression Algorithm Based on Block Truncation Coding and Improved QPIA" *Quantum Information Processing*, 21(5), 170.

[31] Le, P. Q., Dong, F., & Hirota, K. (2011). "A Flexible Representation of Quantum Images for Polynomial Preparation, Image Compression, and Processing "*Quantum Information Processing*, 10(1), 63–84.

[32] Li, H., & Deng, Y. (2019). "NEQR-based Image Encryption and Compression Algorithm Using Chaotic Maps" *Quantum Information Processing*, 18(3), 92.