A color image quantum encryption using NCQI representation

Article · July 2024

2 authors:

Achraf Abdelghafour Zemate
Université Ibn Tofail

M B SEDRA
Université Ibn Tofail

MULTIDISCIPLINARY SCIENCE JOURNAL

SHORT COMMUNICATION
Published Online: July 1, 2024
https://doi.org/10.31893/multiscience.2025007

A color image quantum encryption using NCQI representation

Zemate Achraf Abdelghafour[a] ✉ | **Sedra Moulay Brahim**[a]

[a]Department of Physics, Ibn Tofail University, Kenitra, Morocco.

Abstract In the digital, networked and visual age, the image has become the key medium for conveying information and knowledge. Image security has attracted increasing attention as the operation, sharing and communication in various fields. However, with the widespread use of networks, the security of image transmission faces serious challenges, including unauthorized access, tampering, and interception by malicious attackers. Traditional cryptographic methods play a limited role in image security in the cyber age. With the development of quantum computing and quantum communication, quantum image encryption has emerged, and it fully protects the image security from the perspective of quantum mechanics. When the image is encrypted in the quantum state, due to the quantum properties , quantum image encryption becomes extremely secure. As a result, it is impossible for classical computer technology to decode the encrypted images. Quantum Image Encryption not only protects against image theft and tampering but also enables secure image transmission.In this paper, we present a method for quantum encryption of color images based on NCQI representation and modification of RGB pixel positions and their values. In several steps, using NCQI representation and some quantum logic gates, we can identify the quantum state of the image and modify the RGB pixel values and positions. By calculating several parameters, we conclude this study with a statistical evaluation that proves the effectiveness and strength of our method. This research contributes to the burgeoning field of quantum cryptography by introducing a novel method tailored specifically for color image encryption, thereby advancing the capabilities of quantum secure communication protocols.

Keywords: quantum image representation, quantum encryption, quantum encryption circuit, quantum computing

1. Introduction

Quantum technologies use quantum mechanics to advance communication and cryptography (Abd-El-Atty et al., 2018). Current communications may also include sharing images that contain sensitive information. It is important to ensure the security of private records to prevent misuse, and the protection of multimedia data is a major challenge. Moreover, quantum image cryptography remains one of the best techniques for guaranteeing this operation (Naseri et al., 2018). For quantum encryption, quantum image representation, which allows the representation of image data using quantum states, is an important step (J. Wang et al., 2019). Several quantum representations of quantum images have been established: the Qubit lattice (Venegas-Andraca & Bose, 2003), FRQI (Le et al., 2011), NAQSS (Li et al., 2014), SQR (Yuan et al., 2014), QUALPI (Zhang, Lu, Gao, & Xu, 2013), NEQR (Zhang, Lu, Gao, & Wang, 2013), MCQI (Sun et al., 2013), GNEQR (Li, Fan, et al., 2019), NCQI (Sang et al., 2017), QRCI (Wang L. et al., 2019), QRMW (ŞahiN & Yilmaz, 2018), QMCR (Abdolmaleky et al., 2017), OQIM (Liu et al., 2019), DRQCI (Wang L. et al., 2020) and others (Su et al., 2020).

Color pixels and their positions are encoded differently in quantum representations, which has implications for different image processing applications and levels of complexity (Su et al., 2021). The quantum encryption of an image varies according to the choice of the quantum image representation and the quantum algorithm used. Several methods of quantum image encryption have been developed in recent years (Li, Chen, et al., 2019; Ye et al., 2021; Mahmoud et al., 2021; Song et al., 2022; Sheng et al., 2022; Zhou & He, 2023) and others. However, the rapid evolution of classical and quantum computers requires the creation and development of new methods of quantum image encryption. Here, using NCQI, we represent the quantum state of a color image and perform encryption.

2. Materials and Methods

2.1. NCQI representation

It is used for color images and is defined by the following expression (Sang et al., 2017):

 Received: March 11, 2024 | Accepted: June 3, 2024

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

$|c(y, x)\rangle$ is the color value corresponding to the pixel defined by (y,x) vertical or horizontal positions, and it may be represented in the form:

$$|c(y,x)\rangle = |\underbrace{R_{q-1}\, R_{q-2}\ldots R_0}_{\text{Red}}\,\underbrace{G_{q-1}\, G_{q-2}\ldots G_0}_{\text{Green}}\,\underbrace{B_{q-1}\, B_{q-2}\ldots B_0}_{\text{Blue}}\rangle \quad (2)$$

With

$y \in [0, 2^n - 1]$, $x \in [0, 2^n - 1]$ and each value of the RGB channel $\in [0, 2^q - 1]$.
$R_{q-1}\, R_{q-2}$ ....R_0 is the binary extension of the R channel.
$G_{q-1}\, G_{q-2}$ ....G_0 is the binary extension of the G channel.
$B_{q-1}\, B_{q-2}$....... B_0 is the binary extension of the B channel.

To store a 2^nx2^n image, we need 2n+3q qubits. For example, for n=2, q=8, the NCQI quantum state is represented by the following equation (Figure 1) (Sang et al., 2017; Su et al., 2020, 2021):

$$\begin{aligned} |I\rangle = \frac{1}{4}[&|11111111\ 00000000\ 00000000\rangle \otimes (|0000\rangle+|0001\rangle+|0100\rangle+|0101\rangle) \\ &+|00000000\ 11111111\ 00000000\rangle \otimes (|0010\rangle+|0011\rangle+|0110\rangle+|0111\rangle \\ &+|00000000\ 00000000\ 11111111\rangle \otimes (|1000\rangle+|1001\rangle+|1100\rangle+|1101\rangle) \\ &+|1111111111\ 11111111\ 11111111\rangle \otimes (|1010\rangle+|1011\rangle+|1110\rangle+|1111\rangle)\ ] \end{aligned} \quad (3)$$

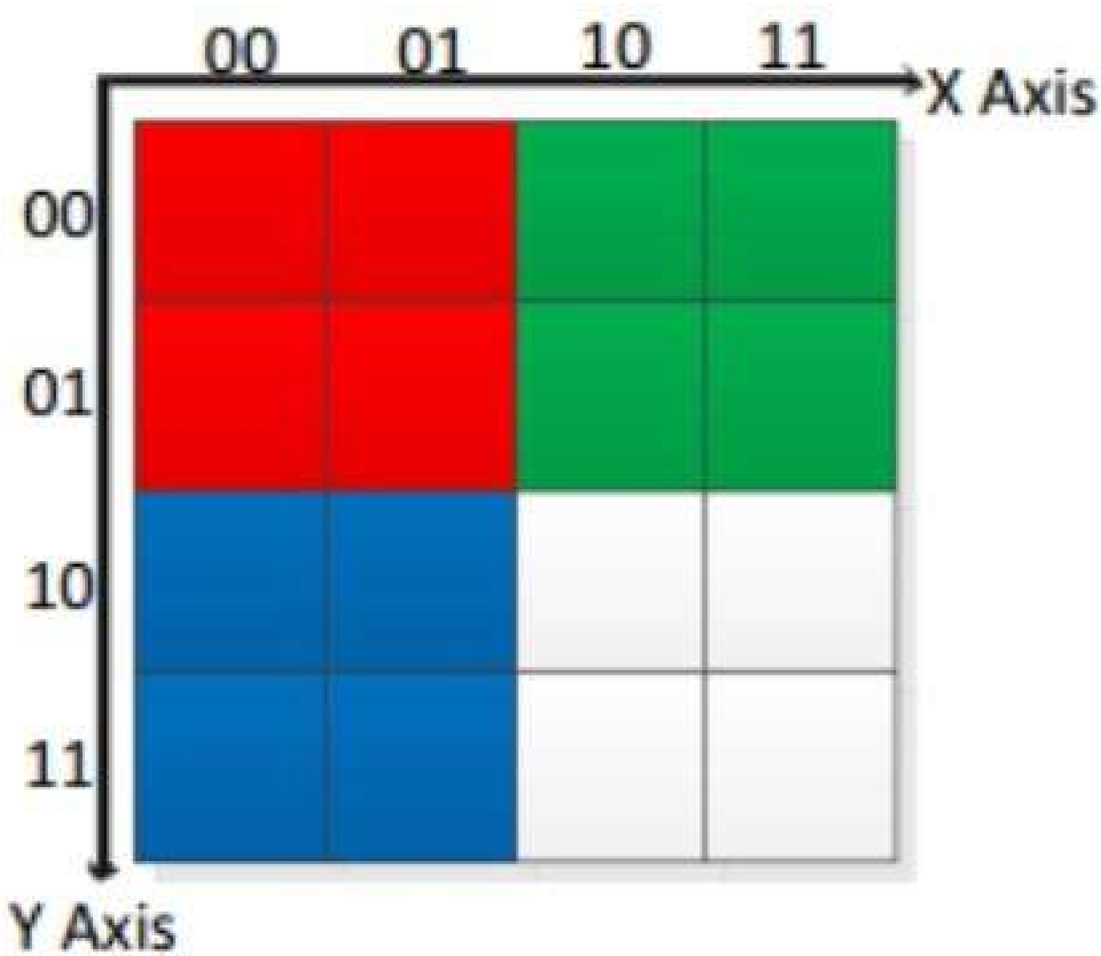


Figure 1 An example of a 4 × 4 color image.

2.2. The proposed image encryption scheme

2.2.1. Steps of preparation of the NCQI representation of the first 4x4 block

Step 1: We take a color image of Lena 128×128 (Figure 2).

Figure 2 Lena image.

Step 2: Then, we extract the matrices of the three RGB channels and use the first block of each matrix to construct the first block of the RGB pixel matrix (Figure 3, Figure 4).

Step 3: Next, we use the NCQI representation to define the quantum state of the first block after converting the pixel values into binary values. We find the expression:

$$\begin{aligned}|\varphi\rangle = \frac{1}{4}[\,&|11100010\ 10000001\ 01101111\rangle \otimes |0000\rangle + |11100010\ 10000010\ 01101011\rangle \otimes |0001\rangle \\ &+|11100000\ 10000011\ 01101100\rangle \otimes |0010\rangle + |11100011\ 10000011\ 01101110\rangle \otimes |0011\rangle \\ &+|11100011\ 10000110\ 01110100\rangle \otimes |0100\rangle + |11100010\ 10000111\ 01111010\rangle \otimes |0101\rangle \\ &+|11100000\ 10000001\ 01101101\rangle \otimes |0110\rangle + |11100001\ 10001001\ 10000000\rangle \otimes |0111\rangle \\ &+|11100010\ 10001000\ 01111010\rangle \otimes |1000\rangle + |11100010\ 10000110\ 01110110\rangle \otimes |1001\rangle \\ &+|11011111\ 10000110\ 01110100\rangle \otimes |1010\rangle + |11100001\ 10000111\ 01110111\rangle \otimes |1011\rangle \\ &+|11100001\ 10000011\ 01101010\rangle \otimes |1100\rangle + |11100001\ 10000011\ 01101111\rangle \otimes |1101\rangle \\ &|11100010\ 10000010\ 01101010\rangle \otimes |1110\rangle + |11100010\ 10000001\ 01101011\rangle \otimes |1111\rangle\,] \qquad (4)\end{aligned}$$

2.2.2. Quantum encryption circuit

We perform two perturbations:

- Changing the 4 qubits representing the pixel position (y,x).
- Changing the 24 qubits representing the RGB pixel values.

The circuits are established using the quantum gates NOT, CNOT and TOFFOLI and SWAP (Figure 5, Figure 6).

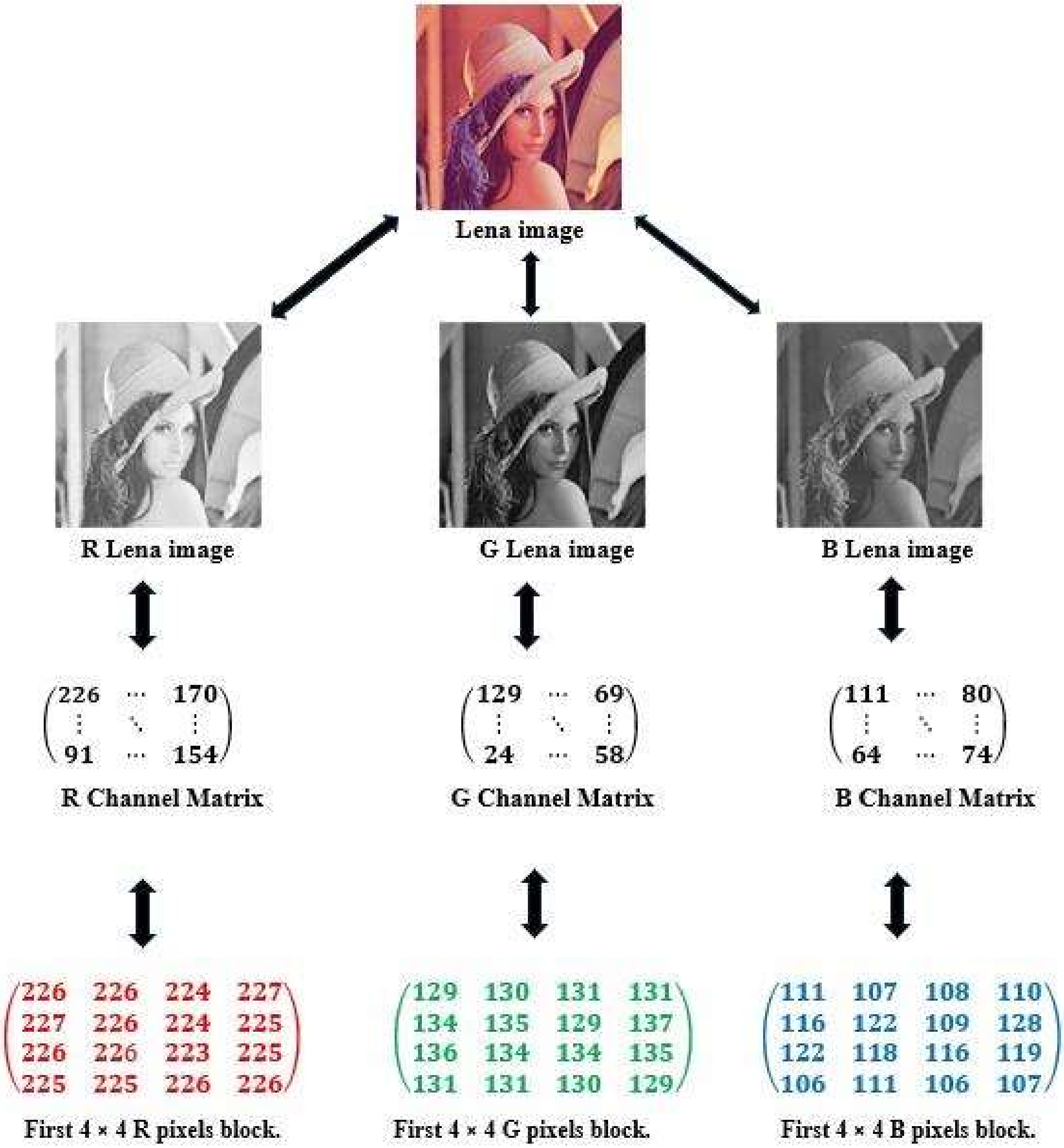
3. Results and discussion

3.1. Encryption result

We obtain the matrix (Figure 7) and the state of the first block:

$$\begin{aligned}|\varphi_E\rangle = \frac{1}{4}[\,&|00000000\ 00011011\ 00101110\rangle \otimes |0000\rangle + |01011010\ 11111111\ 11111111\rangle \otimes |0001\rangle \\ &+|11111111\ 01111101\ 11000010\rangle \otimes |0010\rangle + |11111111\ 01000100\ 10001011\rangle \otimes |0011\rangle \\ &+|00001000\ 11111111\ 11111111\rangle \otimes |0100\rangle + |10111001\ 11111111\ 11101110\rangle \otimes |0101\rangle \\ &+|11111111\ 10101111\ 11111111\rangle \otimes |0110\rangle + |00000000\ 11111111\ 00000000\rangle \otimes |0111\rangle\end{aligned}$$

$$+|00000000\ 01010000\ 10101011\rangle \otimes |1000\rangle + |00000000\ 00110010\ 00000000\rangle \otimes |1001\rangle$$
$$+|11111111\ 11101001\ 11000101\rangle \otimes |1010\rangle + |00000000\ 10110010\ 11110100\rangle \otimes |1011\rangle$$
$$+|00000000\ 11111111\ 00000010\rangle \otimes |1100\rangle + |10111011\ 11111111\ 11101100\rangle \otimes |1101\rangle$$
$$+|00000000\ 00000000\ 01001010\rangle \otimes |1110\rangle + |11111111\ 10111000\ 00000000\rangle \otimes |1111\rangle\,] \quad (5)$$



$$\begin{pmatrix} 226 & \cdots & 170 \\ \vdots & \ddots & \vdots \\ 91 & \cdots & 154 \end{pmatrix} \quad \begin{pmatrix} 129 & \cdots & 69 \\ \vdots & \ddots & \vdots \\ 24 & \cdots & 58 \end{pmatrix} \quad \begin{pmatrix} 111 & \cdots & 80 \\ \vdots & \ddots & \vdots \\ 64 & \cdots & 74 \end{pmatrix}$$

$$\begin{pmatrix} 226 & 226 & 224 & 227 \\ 227 & 226 & 224 & 225 \\ 226 & 226 & 223 & 225 \\ 225 & 225 & 226 & 226 \end{pmatrix} \quad \begin{pmatrix} 129 & 130 & 131 & 131 \\ 134 & 135 & 129 & 137 \\ 136 & 134 & 134 & 135 \\ 131 & 131 & 130 & 129 \end{pmatrix} \quad \begin{pmatrix} 111 & 107 & 108 & 110 \\ 116 & 122 & 109 & 128 \\ 122 & 118 & 116 & 119 \\ 106 & 111 & 106 & 107 \end{pmatrix}$$

Figure 3 Steps of extracting the first block RGB pixel matrix.

$$\begin{pmatrix} (226,129,111) & (226,130,107) & (224,131,108) & (227,131,110) \\ (227,134,116) & (226,135,122) & (224,129,109) & (225,137,128) \\ (226,136,122) & (226,134,118) & (223,134,116) & (225,135,119) \\ (225,131,106) & (225,131,111) & (226,130,106) & (226,129,107) \end{pmatrix}$$

Figure 4 First block RGB pixel matrix.

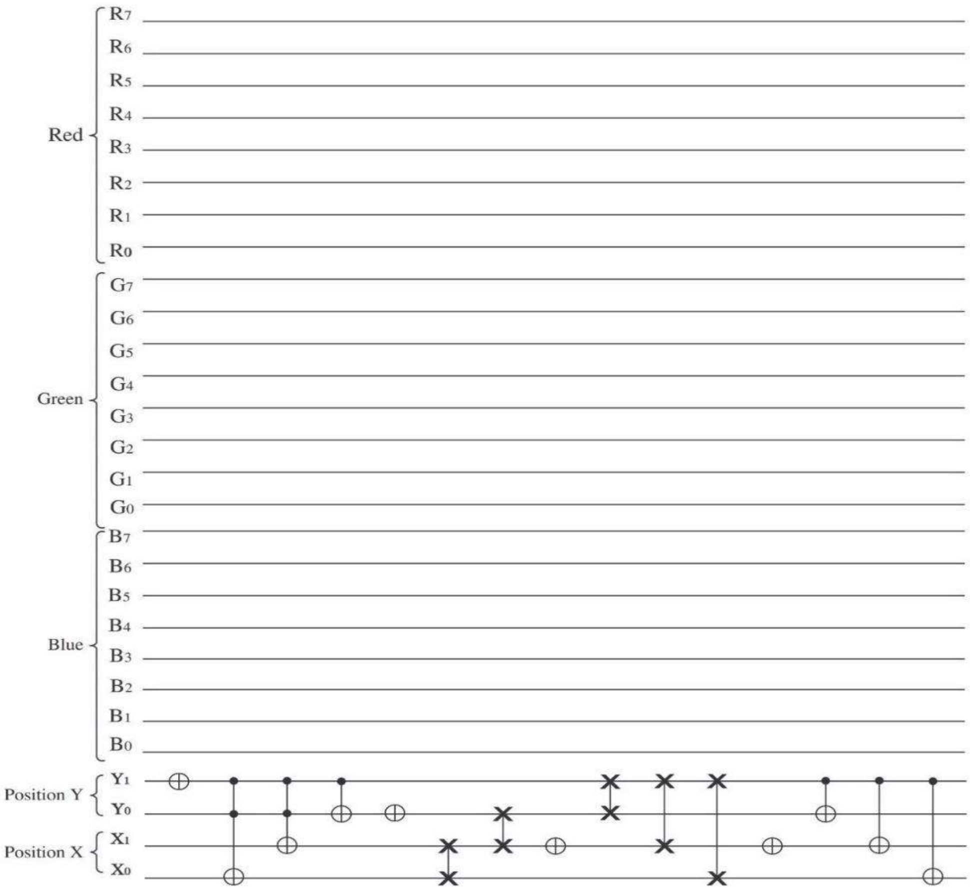


Figure 5 Quantum encryption circuit that changes pixel positions.

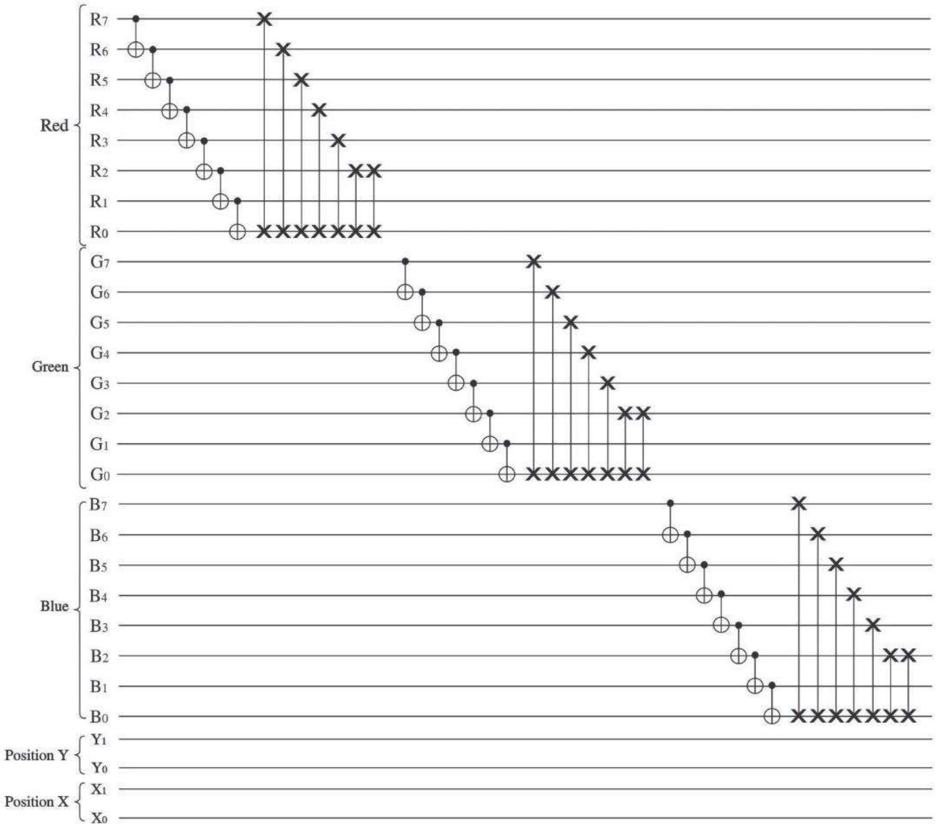


Figure 6 Quantum circuit encryption that changes the pixel values.

$$\begin{pmatrix} (0,27,46) & (90,255,255) & (255,125,194) & (255,68,139) \\ (8,255,255) & (185,255,238) & (255,175,255) & (0,255,0) \\ (0,80,171) & (0,50,0) & (255,233,197) & (0,178,244) \\ (0,255,0) & (187,255,236) & (0,0,74) & (255,184,0) \end{pmatrix}$$

Figure 7 First encrypted block RGB pixel matrix.

Then, we do the same for the other blocks. After concatenating all the blocks, we obtain the encrypted image (Figure 8).

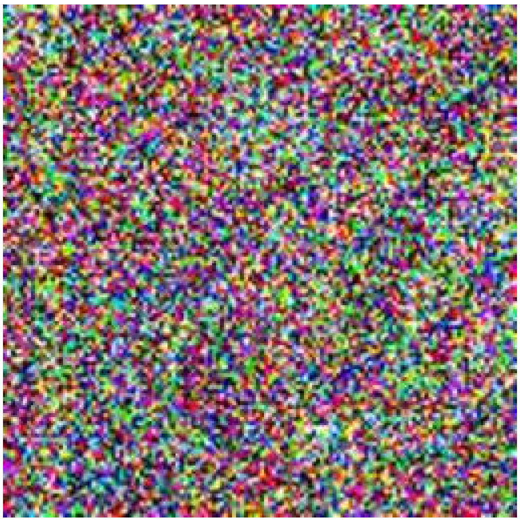


Figure 8 Proposed Lena encrypted image.

3.2. Statistical analysis

3.2.1. Histogram

It is used to show the distribution of pixel values (Le et al., 2011; Li et al., 2014). It is established according to the three RGB channels (Figure 9).

The histograms of encrypted images are nearly uniform, whereas the histograms of the original images are considerably different (Li, Chen, et al., 2019).

3.2.2. MSE

The mean squared error is a measurement of the similarity between the pixels of the original image and the pixels of the encrypted image (Heidari et al., 2019) (Choudhary & Jb, 2014). It is calculated using the following equation:

$$\mathrm{MSE} = \frac{1}{\mathrm{M} \times \mathrm{N}} \sum_{x=1}^{\mathrm{M}} \sum_{y=1}^{\mathrm{N}} (\mathrm{I}(x,y) - \mathrm{I}'(x,y))^2 \qquad (6)$$

With

I(x, y): original image and I′(x, y): encrypted image
M×N: size of the image and x, y: pixel position.

Table 1 shows the found MSE values according to the RGB channels and those of the two previous results.

According to the MSE values, our values are higher than those of the other references, which indicates that the original and encrypted images are very different (Mahmoud et al., 2021) and that our encryption method is efficient and withstands attacks.

3.2.3. NPCR

Using the NPCR, we can estimate how changing the pixel values will affect the analogous original image (EL-Latif et al., 2020). A high NPCR indicates that the encryption system is more resistant to differential attacks (Liang et al., 2023). The NPCR is calculated by:

$$\mathrm{NPCR} = \frac{\sum_{x,y} D(x,y)}{N \times M} \times 100\% \qquad (7)$$

With

$$D(x,y) = \begin{cases} 0 & \text{if } I_O(x,y) = I_E(x,y) \\ 1 & \text{if } I_O(x,y) \neq I_E(x,y) \end{cases} \qquad (8)$$

M×N: size of the image

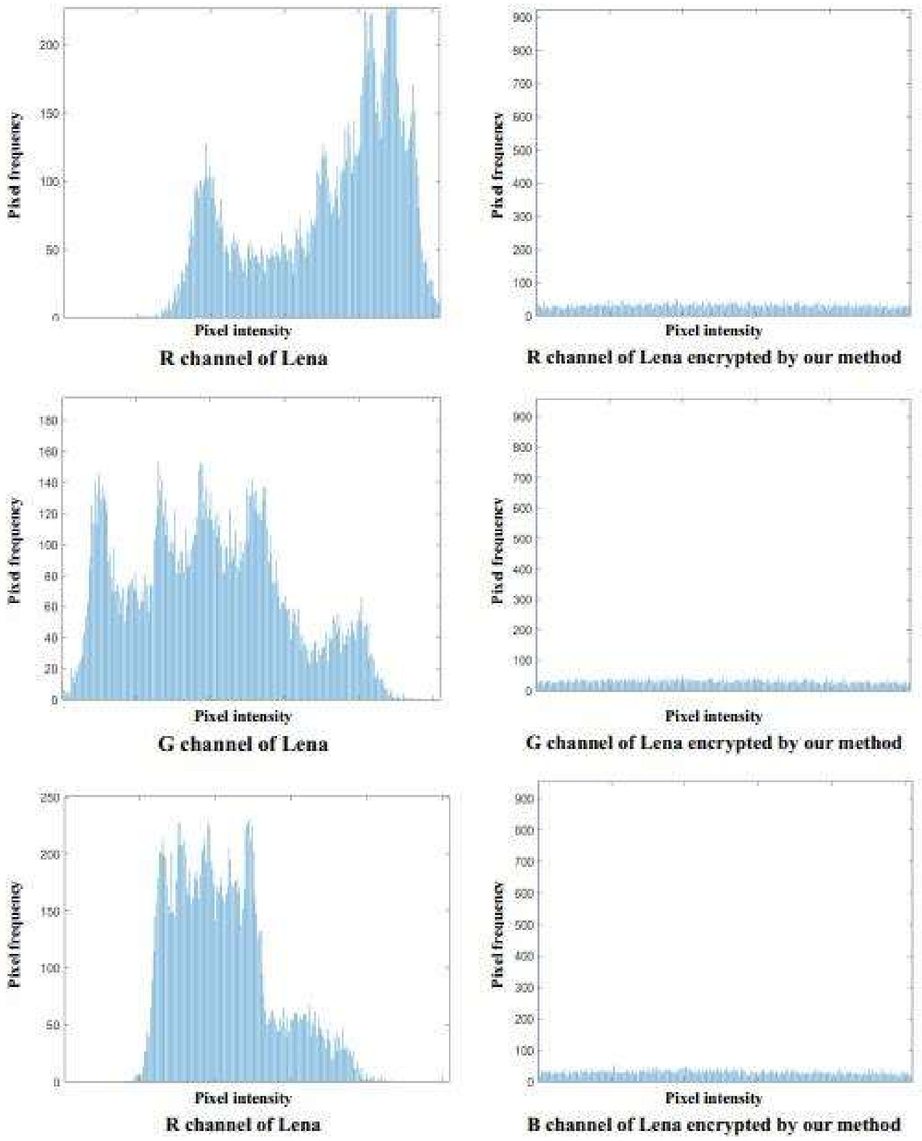


Figure 9 Histograms of each RGB channel in the original image and the encrypted image.

Table 1 Comparison of the MSEs between our scheme and other results.

Image	MSE per channel		
	R	G	B
Image encryption for Lena in (Wang et al., 2020)	9.117E3	9.810E3	1.068E4
Image encryption for Lena in (Rfifi et al., 2021)	9.827E3	1.0481E4	4.108E4
Our proposed image encryption for Lena	1.4975E4	1.2564E4	1.4974E4

Table 2 shows the NPCRs found and some other results.

Compared with other values, our NPCR is the highest, which indicates that there are more changes in the image that result in a large number of pixels being modified in the encrypted image (Ma et al., 2022). This shows good sensitivity to modification and therefore good resistance to certain cryptographic attacks.

Table 2 Comparison of the NPCRs between our scheme and other results.

Image	NPCR (%)
Image encryption for Lena in (Heidari et al., 2019)	99.6093
Image encryption for Lena in (EL-Latif et al., 2020)	99.5987
Image encryption for Lena in (Abdullah & Mahdi, 2022)	99.6205
Our proposed image encryption for Lena	99.6521

3.2.4. Correlation coefficient

This coefficient is a crucial indicator of the effectiveness of image encryption. It measures the degree of similarity between two pixels (Shang & Xu, 2024). It is defined by:

$$r = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}(V_{ij}-\overline{V})(W_{ij}-\overline{W})}{\sqrt{(\sum_{i=1}^{M}\sum_{j=1}^{N}(V_{ij}-\overline{V})^2)(\sum_{i=1}^{M}\sum_{j=1}^{N}(W_{ij}-W)^2)}} \quad (9)$$

With

V_{ij}: the pixels of the original and encrypted image
W_{ij}: the pixels of the encrypted image
$\overline{V}$ and $\overline{W}$ are the average values of Vij and W_{ij}

Table 3 compares our correlation values in the H, V and D directions with previous results.

According to the table, the comparison of our correlation coefficient values with the values of other studies shows that they are close to zero, which indicates that there is no similarity between the pixels of the original and encrypted images (Jiang & Yang, 2023; Ye, 2010).

Table 3 Correlation values using our encryption and those of other previous results.

Image	Correlation		
	Horizontal	Vertical	Diagonal
Image encryption for Lena in (Heidari et al., 2019)	0.0199	- 0.0077	- 0.0102
Image encryption for Lena in (Li et al., 2019)	0.1356	-0.0165	-0.2003
Our proposed image encryption for Lena	0.0114	0.011567	0.0060

4. Conclusions

In this article, a new technique for quantum encryption of color images, which is based on using the NCQI representation by applying two successive operations, including changing RGB pixel positions and changing RGB pixel values, is studied. To evaluate our studied method, we used the MATLAB environment to display the histograms and calculate the MSE, NPCR and correlation coefficients.

The results show that our encryption approach is effective and can withstand attacks. The proposed method may be suitable for providing an effective solution for large-color image encryption applications.

Ethical considerations

Not applicable.

Conflict of interest

The authors declare no conflicts of interest.

Funding

This research did not receive any financial support.

References

Abd-El-Atty, B., Venegas-Andraca, S. E., & Abd El-Latif, A. A. (2018). Quantum Information Protocols for Cryptography. In A. E. Hassanien, M. Elhoseny, & J. Kacprzyk (Eds.), *Quantum Computing :An Environment for Intelligent Large Scale Real Application* (pp. 3–23). Springer International Publishing.

Abdolmaleky, M., Naseri, M., Batle, J., Farouk, A., & Gong, L.-H. (2017). Red–Green-Blue multichannel quantum representation of digital images. *Optik, 128*, 121–132. https://doi.org/10.1016/j.ijleo.2016.09.123

Abdullah, A. A., & Mahdi, S. S. (2022). Implementing quantum image security algorithm based on geometric transformation and quantum random number generation. *Journal of Engineering Science and Technology, 17*(5), 3570–3582.

Choudhary, R., & Jb, A. (2014). Secure Image Transmission and Evaluation of Image Encryption. *International Journal of Innovative Science, Engineering & Technology, 1*(1), 65–69.

EL-Latif, A. A. A., Abd-El-Atty, B., & Venegas-Andraca, S. E. (2020). Controlled alternate quantum walk-based pseudorandom number generator and its application to quantum color image encryption. *Physica A: Statistical Mechanics and Its Applications, 547*, 123869. https://doi.org/10.1016/j.physa.2019.123869

Heidari, S., Vafaei, M., Houshmand, M., & Tabatabaey-Mashadi, N. (2019). A dual quantum image scrambling method. *Quantum Information Processing, 18*(1), 9. https://doi.org/10.1007/s11128-018-2122-4

https://doi.org/10.1088/1757-899X/1172/1/012011

https://doi.org/10.1109/TCSI.2018.2853655
https://doi.org/10.3389/fphy.2022.1028630

Jiang, M., & Yang, H. (2023). Image Encryption Algorithm Using Multi-Level Permutation and Improved Logistic–Chebyshev Coupled Map. *Information, 14*(8), 456. https://doi.org/10.3390/info14080456

Le, P. Q., Dong, F., & Hirota, K. (2011). A flexible representation of quantum images for polynomial preparation, image compression, and processing operations. *Quantum Information Processing, 10*(1), 63–84. https://doi.org/10.1007/s11128-010-0177-y

Li, H.-S., Chen, X., Song, S., Liao, Z., & Fang, J. (2019). A Block-Based Quantum Image Scrambling for GNEQR. *IEEE Access, 7*, 138233–138243. https://doi.org/10.1109/ACCESS.2019.2942986

Li, H.-S., Fan, P., Xia, H.-Y., Peng, H., & Song, S. (2019). Quantum Implementation Circuits of Quantum Signal Representation and Type Conversion. *IEEE Transactions on Circuits and Systems I: Regular Papers, 66*(1), 341–354.
Li, H.-S., Zhu, Q., Zhou, R.-G., Song, L., & Yang, X. (2014). Multidimensional color image storage and retrieval for a normal arbitrary quantum superposition state. *Quantum Information Processing, 13*(4), 991–1011. https://doi.org/10.1007/s11128-013-0705-7

Liang, J., Song, Z., Sun, Z., Lv, M., & Ma, H. (2023). Coupling Quantum Random Walks with Long- and Short-Term Memory for High Pixel Image Encryption Schemes. *Entropy, 25*(2), 353. https://doi.org/10.3390/e25020353

Liu, X., Xiao, D., Huang, W., & Liu, C. (2019). Quantum Block Image Encryption Based on Arnold Transform and Sine Chaotification Model. *IEEE Access, 7*, 57188–57199. https://doi.org/10.1109/ACCESS.2019.2914184

Ma, Y., Yu, F.-F., Gong, L.-H., & Zou, W.-P. (2022). Fast quantum image encryption scheme based on multilayer short memory fractional order Lotka-Volterra system and dual-scale triangular map. *Frontiers in Physics,10*, 1028630.

Mahmoud, M. A., Mekkawy, T., & Elbayoumy, A. D. (2021). Enhanced image encryption algorithm by quantum key distribution. *IOP Conference Series: Materials Science and Engineering, 1172*(1), 012011.

Naseri, M., Abdolmaleky, M., Laref, A., Parandin, F., Celik, T., Farouk, A., Mohamadi, M., & Jalalian, H. (2018). A new cryptography algorithm for quantum images. Optik, 171, 947–959. https://doi.org/10.1016/j.ijleo.2018.06.113

Rfifi, S., Maafiri, A., Chougdali, K., & Gueddana, A. (2021). A new efficient model of quantum image cryptography based on sampled GNEQR storage presentation. *Journal of the Korean Physical Society, 78*(7), 618–626. https://doi.org/10.1007/s40042-021-00065-7

ŞahiN, E., & Yilmaz, İh. (2018). QRMW: Quantum representation of multi wavelength images. *TURKISH JOURNAL OF ELECTRICAL ENGINEERING & COMPUTER SCIENCES, 26*(2), 768–779. https://doi.org/10.3906/elk-1705-396

Sang, J., Wang, S., & Li, Q. (2017). A novel quantum representation of color digital images. *Quantum Information Processing, 16*(2), 42. https://doi.org/10.1007/s11128-016-1463-0

Shang, J., & Xu, X. (2024). Research on a double image security transmission algorithm of image encryption and hiding. *Measurement: Sensors, 31*, 100942. https://doi.org/10.1016/j.measen.2023.100942

Sheng, Y., Li, J., Di, X., Li, X., & Xu, R. (2022). An Image Encryption Algorithm Based on Complex Network Scrambling and Multi-Directional Diffusion. *Entropy, 24*(9), 1247. https://doi.org/10.3390/e24091247

Song, X., Chen, G., & Abd El-Latif, A. A. (2022). Quantum Color Image Encryption Scheme Based on Geometric Transformation and Intensity Channel Diffusion. *Mathematics, 10*(17), 3038. https://doi.org/10.3390/math10173038

Su, J., Guo, X., Liu, C., & Li, L. (2020). A New Trend of Quantum Image Representations. *IEEE Access, 8*, 214520–214537. https://doi.org/10.1109/ACCESS.2020.3039996

Su, J., Guo, X., Liu, C., Lu, S., & Li, L. (2021). An improved novel quantum image representation and its experimental test on IBM quantum experience. *Scientific Reports, 11*(1), 13879. https://doi.org/10.1038/s41598-021-93471-7

Sun, B., Iliyasu, A. M., Yan, F., Dong, F., Hirota, K., & Department of Computational Intelligence and Systems Science, Tokyo Institute of Technology, G3-49, 4259 Nagatsuta, Midori-ku, Yokohama 226-8502, Japan. (2013). An RGB Multi-Channel Representation for Images on Quantum Computers. *Journal of Advanced Computational Intelligence and Intelligent Informatics, 17*(3), 404–417. https://doi.org/10.20965/jaciii.2013.p0404

Venegas-Andraca, S. E., & Bose, S. (2003). Storing, processing, and retrieving an image using quantum mechanics .In E. Donkor, A. R. Pirich, & H. E. Brandt (Eds.),(p. 137). https://doi.org/10.1117/12.485960

Wang, J., Geng, Y.-C., Han, L., & Liu, J.-Q. (2019). Quantum Image Encryption Algorithm Based on Quantum Key Image. *International Journal of Theoretical Physics, 58*(1), 308–322. https://doi.org/10.1007/s10773-018-3932-y

Wang, L., Ran, Q., & Ma, J. (2020). Double quantum color images encryption scheme based on DQRCI. *Multimedia Tools and Applications, 79*(9–10), 6661–6687. https://doi.org/10.1007/s11042-019-08514-z

Wang, L., Ran, Q., Ma, J., Yu, S., & Tan, L. (2019). QRCI: A new quantum representation model of color digital images. *Optics Communications, 438*, 147–158. https://doi.org/10.1016/j.optcom.2019.01.015

Ye, G. (2010). Image scrambling encryption algorithm of pixel bit based on chaos map. *Pattern Recognition Letters, 31*(5), 347–354. https://doi.org/10.1016/j.patrec.2009.11.008

Ye, G., Wu, H., Jiao, K., Mei, D., & Faculty of Mathematics and Computer Science, Guangdong Ocean University, Zhanjiang 524088, China. (2021). Asymmetric image encryption scheme based on the Quantum logistic map and cyclic modulo diffusion. *Mathematical Biosciences and Engineering, 18*(5), 5427–5448. https://doi.org/10.3934/mbe.2021275

Yuan, S., Mao, X., Xue, Y., Chen, L., Xiong, Q., & Compare, A. (2014). SQR: A simple quantum representation of infrared images. *Quantum Information Processing, 13*(6), 1353–1379. https://doi.org/10.1007/s11128-014-0733-y

Zhang, Y., Lu, K., Gao, Y., & Wang, M. (2013). NEQR: A novel enhanced quantum representation of digital images. *Quantum Information Processing, 12*(8), 2833–2860. https://doi.org/10.1007/s11128-013-0567-z

Zhang, Y., Lu, K., Gao, Y., & Xu, K. (2013). A novel quantum representation for log-polar images. *Quantum Information Processing, 12*(9), 3103–3126. https://doi.org/10.1007/s11128-013-0587-8

Zhou, X., & He, J. (2023). Quantum Image Encryption Algorithm Incorporating Bit-plane Color Representation and Real Ket Model. *Journal of Cyber Security and Mobility 12*(5), 757–784. https://doi.org/10.13052/jcsm2245-1439.1257