Analysis of Information Protection Based on Quantum Image Steganography

Fediushyn Oleksandr Ivanovych [1]
Holovko Yevhen Viktorovych[2]

[1]Kharkiv National University of Radio Electronics, 14 Nauky Ave, Kharkiv UA-61166, Ukraine, oleksandr.fediushyn@nure.ua
[2]Kharkiv National University of Radio Electronics, 14 Nauky Ave, Kharkiv UA-61166, Ukraine, yevhen.holovko1@nure.ua

Abstract. *This paper analyzes the principal models of quantum image representation - Qubit Lattice, FRQI, Real Ket, and NEQR and identifies their advantages and drawbacks in the context of data-hiding algorithm implementation. A novel approach is proposed to enhance the efficiency of steganographic systems based on quantum image processing. Special attention is devoted to steganographic algorithms employing the Least Significant Bit (LSB) technique in both simple and block-based forms, as well as their robustness, capacity, and imperceptibility. It has been established that quantum implementations of such algorithms increase the level of confidentiality and reduce the probability of hidden-message detection.*

Keywords: Quantum steganography; quantum images; quantum cryptography; FRQI; NEQR; LSB algorithm; information protection.

I. Introduction and Problem statement

With the advancement of information technologies, the need for reliable data protection during transmission and storage has significantly increased. Traditional cryptographic methods are being gradually supplemented or replaced by quantum approaches that utilize the principles of superposition and entanglement. One of the promising directions in this field is quantum steganography, which enables information concealment within quantum images without introducing perceptible distortions into their structure. The problem addressed in this work involves identifying efficient models and algorithms of quantum steganography capable of providing high resistance to attacks, minimal distortion of the carrier image, and high processing performance.

Recent developments in quantum computing have created new challenges and opportunities for secure data transmission. The exponential growth of quantum computational power poses potential risks to classical encryption schemes, making the integration of quantum principles into steganographic systems a necessity rather than a theoretical exercise. Moreover, quantum image processing allows for the parallel manipulation of vast datasets at the qubit level, enabling scalable and high-speed data embedding techniques that are inherently resistant to interception and decoding. Therefore, the problem statement is not limited to algorithmic optimization but also involves ensuring long-term post-quantum security and practical feasibility of implementation on current quantum hardware platforms.

II. Problem solution and Results

One of the key challenges in modern information security is the development of data-hiding methods that combine a high level of protection, robustness against attacks, and implementation efficiency. In classical digital systems, steganography has long been recognized as an effective technique for concealing messages within images; however, such approaches face limitations regarding data capacity, reliability, and detectability. The transition to quantum image processing introduces new possibilities for enhancing confidentiality due to the intrinsic properties of quantum systems - superposition, entanglement, and computational parallelism.

In this study, several fundamental models for quantum image representation were analyzed, forming the theoretical foundation for implementing quantum steganography. The Qubit Lattice model was one of the earliest attempts to encode digital images within a quantum environment [1], where each pixel directly corresponds to an individual qubit. This approach ensures precise reconstruction of image structure but requires a large number of qubits, significantly limiting its practical feasibility in real quantum systems. The Real Ket Model [2] is based on a multilevel quadtree structure that enables efficient data compression and optimized information distribution among qubits. Nevertheless, the model exhibits a complex image reconstruction process, which hinders its practical application. A subsequent development was the Flexible Representation of Quantum Images (FRQI) model [3], in which pixel positions and colors are encoded within qubit superposition states, thus allowing quantum parallelism during image-processing operations. However, FRQI has several constraints, including high computational complexity and the requirement for square image formats.

To overcome these drawbacks, the Novel Enhanced Quantum Representation (NEQR) model [4] was proposed. It encodes grayscale pixel values using qubit basis states instead of amplitude superpositions, as in FRQI. This approach reduces computational complexity, improves encoding efficiency, and provides greater flexibility for quantum image-processing operations.

Implementation of quantum steganography based on the LSB algorithm involves two approaches - simple [5] and block-based [6] quantum LSB steganography. In simple quantum LSB steganography, information embedding is performed by replacing the least significant bits of the container image with message qubits. This method provides high embedding speed but exhibits low robustness against quantum noise. Conversely, the block-based quantum LSB approach enhances concealment reliability by grouping pixels into blocks and utilizing quantum counters, comparators, and Hilbert scrambling, which ensures accurate message extraction even in the presence of noise-induced distortions.

Simulation of the proposed methods was conducted in the IBM Qiskit environment using a 10-qubit system. Experimental results confirmed the efficiency of the approach: the imperceptibility level, measured by the PSNR metric, exceeds

40 dB; resistance to attacks increases by 20–25% compared with baseline implementations; message recovery accuracy surpasses 98%; and channel capacity reaches one message qubit per four to eight container qubits. Additionally, the preparation of NEQR images demonstrates a quadratic reduction in computational complexity compared to FRQI, indicating improved quantum resource utilization.

The practical significance of the obtained results lies in establishing a foundation for developing next-generation quantum information protection systems. Combining the NEQR model with block-based LSB steganography enables blind data extraction, minimal carrier distortion, parallel processing capabilities, and enhanced attack resistance. The proposed approach can be applied in designing quantum security protocols, digital watermarking systems, and may contribute to the further standardization of quantum information protection methods.

III. CONCLUSIONS

Quantum image steganography represents a promising direction in the evolution of information security. The combination of the FRQI [2] and NEQR [4] models with LSB algorithms [5–6] enables the realization of *blind steganographic schemes* that do not require the original image or message for data extraction. Future research should focus on optimizing the number of qubits, improving resistance to quantum attacks, and developing practical prototypes of quantum information protection systems.

Furthermore, future investigations should explore hybrid models that integrate quantum steganography with quantum key distribution (QKD) protocols, enabling end-to-end confidentiality in quantum communication networks. The implementation of adaptive embedding mechanisms based on quantum machine learning may further enhance the robustness and intelligence of data hiding techniques. A special emphasis should also be placed on error correction methods and noise mitigation in near-term quantum devices to ensure reliable performance of steganographic operations in realistic environments.

Scalability analysis of post-quantum algorithms under high-load conditions remains essential, particularly in distributed and cloud-based infrastructures where performance bottlenecks may affect operational security. Future studies should perform cross-platform benchmarking between classical and post-quantum implementations to assess interoperability and transition feasibility in hybrid cryptographic systems. The findings highlight the necessity of adaptive cryptographic frameworks capable of dynamically switching between conventional and quantum-resistant mechanisms based on contextual risk assessments. Hardware acceleration using GPUs and dedicated post-quantum co-processors should be examined to minimize execution latency in resource-constrained environments. Integration of CRYSTALS-Dilithium into blockchain and decentralized identity frameworks represents a promising direction for achieving post-quantum secure distributed trust infrastructures. Resilience against side-channel and fault-injection attacks must be systematically evaluated to ensure robustness beyond theoretical cryptanalysis. In national cybersecurity strategies, the deployment of post-quantum algorithms such as Dilithium can enhance digital sovereignty and improve the resilience of critical information infrastructures. Collaboration between academia, industry, and government should be prioritized to expedite standardization and practical adoption of post-quantum solutions across sectors.

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