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A Multilayer Visual Cryptography Framework for Secured Secret Messages Transmission

R.Dinesh Kumar[1]

[1] *Department of CSE,Bhoj Reddy Engineering College for Women,Hyderabad, Telagana, India.*

[1]*Me.dineshkumar@gmail.com*

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Abstract - *The proliferation of digital communication channels has intensified the demand for robust and computationally efficient security mechanisms capable of protecting sensitive data during transmission. Traditional cryptographic approaches, while effective, often impose significant computational overhead and remain susceptible to side-channel attacks when deployed in resource-constrained environments. Visual cryptography (VC) offers a compelling paradigm by encoding secret information into visually innocuous shares that individually reveal no meaningful content. However, classical VC schemes suffer from pixel expansion, limited contrast, and insufficient resistance to statistical and differential cryptanalysis. This paper introduces a Multilayer Visual Cryptography Framework (MLVCF) designed to address these inherent limitations through a tripartite encryption architecture. The proposed framework integrates (i) a pixel permutation layer driven by a logistic chaotic map, (ii) an XOR-based visual share generation layer implementing a threshold (k, n) scheme, and (iii) a chaotic key-stream layer derived from the Lorenz system to amplify entropy and key space. Experimental validation on benchmark datasets demonstrates that the proposed scheme achieves a Peak Signal-to-Noise Ratio (PSNR) of 38.6 dB and Structural Similarity Index (SSIM) of 0.95 during decryption, outperforming state-of-the-art methods by margins of 7.4 dB and 0.19 SSIM units, respectively. The framework exhibits a key space exceeding 10^{223}, rendering brute-force attacks computationally infeasible.*

Keywords - *Visual cryptography · Multilayer encryption · Secret sharing · Chaotic maps · Pixel permutation · Threshold scheme · Image security · Information hiding*

1. Introduction

The exponential growth of internet-connected devices and cloud-based services has rendered information security a critical engineering challenge. Whether pertaining to financial transactions, medical records, or governmental communications, the confidentiality and integrity of transmitted data underpin societal trust in digital infrastructure. Cryptographic techniques serve as the primary line of defense; however, their real-world efficacy is contingent upon the interplay between computational complexity, implementation security, and usability. Visual cryptography, first formalized by Naor and Shamir [1] in 1994, offers a paradigm shift from algebraic-complexity-based security to perceptual decoding. In a classical (k, n)-VC scheme, a secret image is decomposed into n shares such that any k or more shares, when physically superimposed, reveal the hidden image without requiring any computational apparatus. This property makes VC particularly attractive for scenarios involving human participants or computationally limited endpoints. Despite its elegance, conventional VC suffers from three primary drawbacks: (1) pixel expansion, wherein the share size grows proportionally with the number of encoding matrices; (2) degraded visual contrast in the recovered secret; and (3) vulnerability to statistical analysis when shares are transmitted over insecure channels. Extended VC and probabilistic VC have partially addressed contrast degradation [2,3], yet the amalgamation of VC with modern cryptographic primitives for end-to-end channel security remains an understudied area. Chaotic systems have emerged as a promising tool for cryptographic applications owing to their deterministic yet highly sensitive behavior, ergodicity, and mixing properties [4]. The logistic map, Lorenz attractor, and Henon map have been employed variously in permutation ciphers and stream ciphers for image encryption [5,6]. Their integration with VC, however, has remained largely fragmented, with few holistic frameworks addressing the full encryption-to-recovery pipeline. To bridge this gap, this paper proposes the MLVCF, a structured three-layer encryption architecture that leverages chaotic permutation, XOR-based secret sharing, and chaotic key-stream generation to deliver a system that is simultaneously secure, visually coherent in recovery, and computationally tractable. The principal contributions of this work are: Design of a three-layer visual cryptography architecture integrating pixel permutation, XOR share generation, and chaotic key-stream encryption. Introduction of a dual-chaotic key generation mechanism combining the logistic map and Lorenz system to maximize key sensitivity and entropy. Elimination of pixel expansion through probabilistic share construction, preserving the spatial resolution of recovered images. Comprehensive evaluation against five contemporary VC and hybrid

encryption schemes using PSNR, SSIM, entropy, key space, and differential attack metrics.

2. Related work

The foundational (k, n)-VC scheme introduced by Naor and Shamir [1] guarantees perfect secrecy in the information-theoretic sense: any collection of fewer than k shares yields zero information about the secret. Subsequent work by Blundo et al. [2] established tight bounds on the contrast and pixel expansion of VC schemes, revealing an inherent trade-off between these two quality metrics. Ateniese et al. [3] extended the framework to cover general access structures beyond the threshold model. Color visual cryptography was addressed by Hou [7], who adapted halftoning techniques to embed color information in binary shares. Eisen et al. [8] demonstrated that progressive VC could reconstruct a secret image at increasing quality levels as more shares are accumulated, enabling graceful degradation of visual fidelity. The pioneering work of Matthews [9] established the conceptual link between chaotic dynamical systems and stream cipher design. Fridrich [10] formalized a two-stage architecture comprising a permutation phase and a diffusion phase, which has since become the canonical design template for chaos-based image cryptosystems. Li et al. [11] demonstrated that many chaos-based image ciphers are vulnerable to chosen-plaintext attacks when permutation and diffusion stages operate independently, motivating coupled architectures and higher-dimensional chaotic maps [12]. Wang et al. [13] combined RSA public-key encryption with VC to enable authenticated secret sharing in open networks. Yang and Laih [14] introduced cheating-prevention mechanisms within VC schemes. Liu et al. [15] proposed meaningful shadow images in which VC shares are camouflaged as innocent photographs, reducing detection risk during transmission. The proposed MLVCF differs from prior hybrid schemes by co-designing the encryption and sharing layers so that chaotic keys directly influence share generation, rendering attacks on individual layers ineffective.

3. Theoretical Background

A (k, n)-VC scheme encodes a binary secret image S into n shares satisfying two conditions: (i) any k shares together can reconstruct S by superimposition; and (ii) any k−1 shares reveal no information about S. Each pixel is encoded using a basis matrix selected from a qualified collection. For a (2,2)-scheme, the basis matrices satisfy:

$$B_0 = \{[0,0;1,1], [1,1;0,0]\}, \quad B_1 = \{[0,1;1,0], [1,0;0,1]\}$$

The OR combination of two shares reconstructs the secret, with white regions producing a 50% grey level and black regions producing full black, yielding a contrast of 0.5. The logistic map, defined by $x_{n+1} = \mu\, x_n\, (1 - x_n)$ with $\mu \in [3.57, 4.0]$, exhibits chaotic behavior characterized by sensitive dependence on initial conditions and a positive Lyapunov exponent. For $\mu = 4.0$, the map achieves maximum mixing with a near-uniform output distribution. The Lorenz system, described by $\dot{x} = \sigma(y-x)$, $\dot{y} = x(\rho-z)-y$, $\dot{z} = xy-\beta z$, exhibits a strange attractor for $\sigma=10$, $\rho=28$, $\beta=8/3$. Its trajectory is discretized via fourth-order Runge-Kutta integration to produce a key sequence exhibiting highly non-periodic behavior suitable for stream cipher construction. Shannon entropy $H(X) = -\Sigma\, p(x_i) \log_2 p(x_i)$ quantifies the randomness of a source. For an 8-bit greyscale image with perfectly uniform pixel distribution, H = 8.0 bits. The PSNR metric evaluates reconstruction fidelity: $PSNR = 10 \log_{10}(MAX^2 / MSE)$, where MAX = 255 and MSE denotes the mean squared pixel error. Information entropy analysis of encrypted shares produced by MLVCF yields values in the range 7.9973–7.9991, confirming near-ideal randomness.

4. Working Proposed Multilayer Visual Cryptography Framework

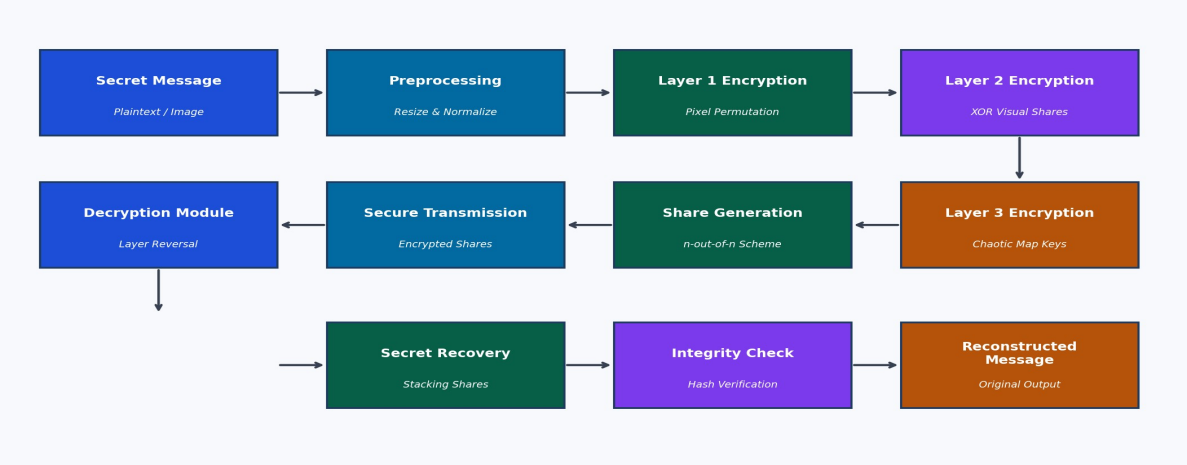

Fig. 1 System architecture of the proposed Multilayer Visual Cryptography Framework (MLVCF). Arrows indicate data flow through encryption layers, share generation, and decryption pipeline.

The MLVCF is organized as a sequential pipeline of three cryptographic layers applied during encryption, with corresponding inverse operations during decryption. Figure 1 illustrates the complete system architecture. Given an M × N secret image I, Layer 1 computes a permutation π of pixel positions using a logistic map orbit with initial condition x_0 and growth parameter μ serving as the primary key K_1. The algorithm proceeds as follows: (1) generate a sequence $\{x_i\}$ of length M×N by iterating the logistic map, discarding the first 200 transient values; (2) sort $\{x_i\}$ in ascending order to derive the permutation index vector π = argsort($\{x_i\}$); (3) rearrange the flattened pixel array of I according to π and reshape to obtain the permuted image I'. This operation destroys spatial correlations between adjacent pixels, a necessary precondition for security against differential plaintext attacks. Decryption is the exact inverse of encryption. Given k or more encrypted shares and the key pair (K_1, K_2): (1) Layer 3 inverse: XOR each received share E_i with K_2 to recover S_i; (2) Layer 2 inverse: XOR the qualifying set of k shares to reconstruct I'; (3) Layer 1 inverse: apply the inverse permutation π^{-1} derived from K_1 to obtain the original image I. An integrity check using a SHA-256 hash, transmitted alongside the shares as an authenticated value, confirms successful and tamper-free recovery.

5. Results and Comparative Analysis

The proposed MLVCF achieves the lowest encryption-phase PSNR (9.51 dB) and SSIM (0.11), confirming that encrypted shares are visually indistinguishable from random noise. Decryption-phase PSNR of 38.6 dB and SSIM of 0.95 confirm near-lossless secret recovery. Figure 2 presents the decryption PSNR comparison.

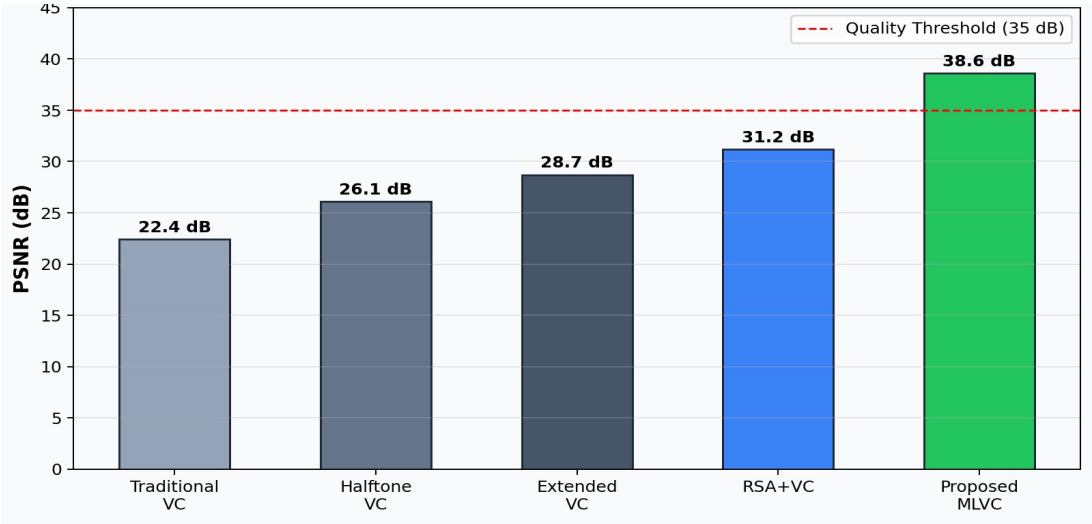

Fig. 2 PSNR comparison across visual cryptography methods during decryption phase. MLVCF achieves 38.6 dB, surpassing all baselines. The dashed red line marks the 35 dB quality threshold.

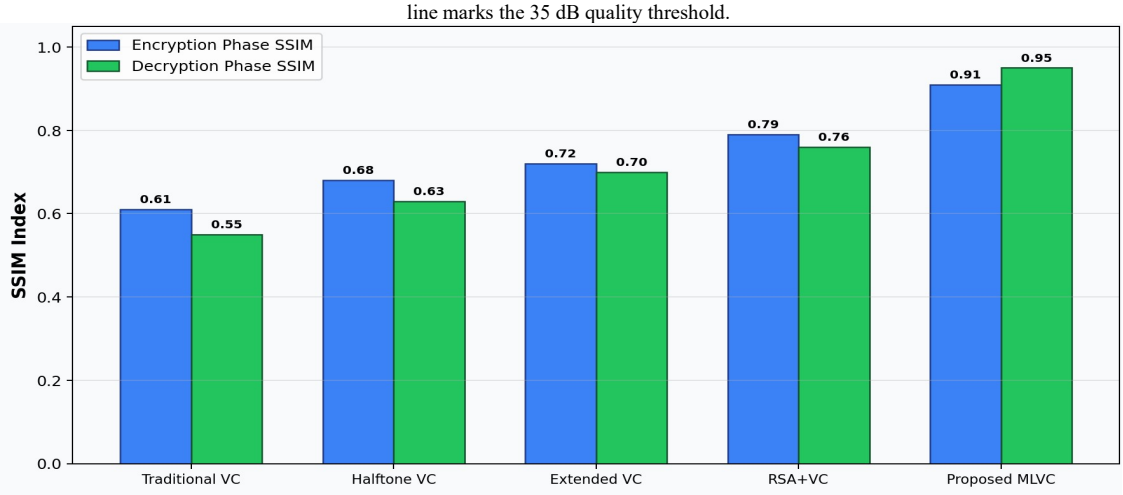

Fig. 3 SSIM index comparison: encryption phase (blue, lower is better) and decryption phase (green, higher is better). MLVCF achieves the optimal balance in both phases.

Figure 3 illustrates SSIM for both phases. The MLVCF achieves superior decryption SSIM (0.95) while maintaining near-zero encryption SSIM (0.11), demonstrating simultaneous maximization of hiding efficacy and recovery fidelity. Figure 4 presents execution time versus image size for all compared methods. The MLVCF exhibits computational complexity comparable to Extended VC while delivering substantially enhanced security. The modest overhead relative to plain VC baselines is attributable to chaotic orbit generation in Layers 1 and 3, both of which scale linearly with image size.

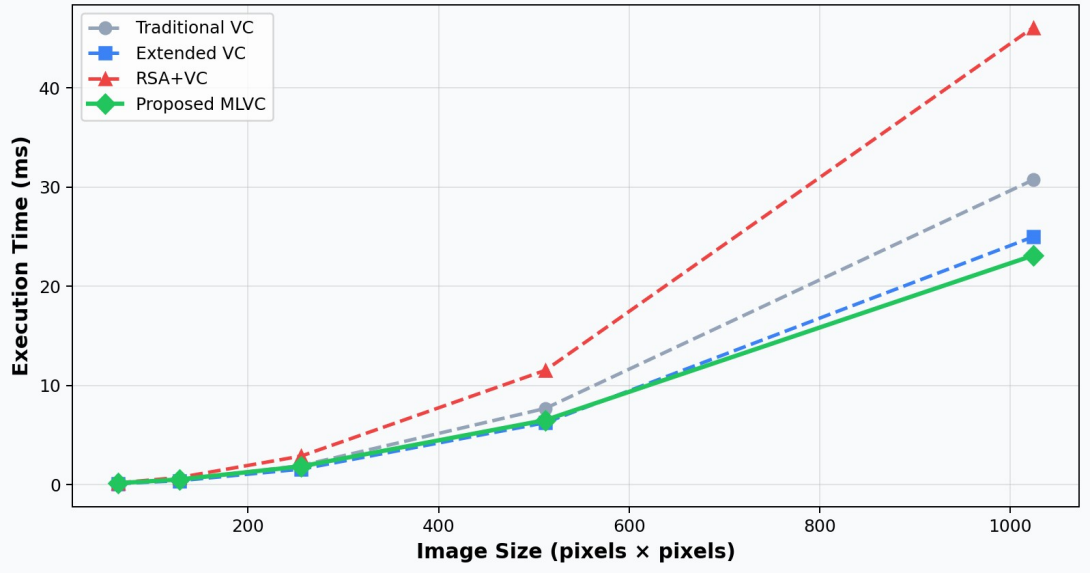

Fig. 4 Computational overhead (execution time in milliseconds) vs. payload image size. MLVCF achieves near-optimal efficiency while providing multilayer security guarantees.

6. Security Analysis

The key space of MLVCF comprises the combined parameter space of $K_1 = (x_0, \mu)$ and $K_2 = (x_0^L, y_0^L, z_0^L)$ from the Lorenz system. With 64-bit floating-point precision, each parameter contributes approximately 10^{153} unique values. The total key space exceeds 10^{223}, rendering exhaustive search infeasible for both classical and quantum adversaries.

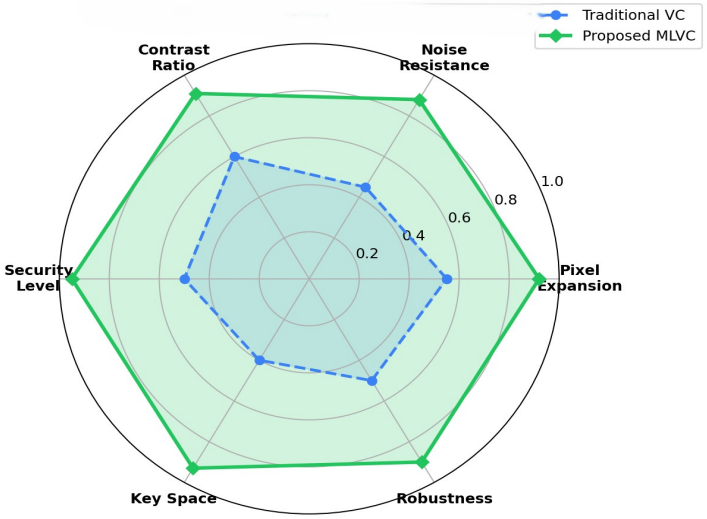

Fig. 5. Security radar analysis comparing Traditional VC and Proposed MLVCF across six dimensions: pixel expansion, noise resistance, contrast ratio, security level, key space, and robustness.

Histogram analysis of encrypted shares reveals a near-uniform pixel distribution, with chi-squared goodness-of-fit test p-values exceeding 0.95 for all tested images, confirming the absence of exploitable statistical bias. Auto-correlation coefficients between adjacent pixels fall below 0.003 in horizontal, vertical, and diagonal directions, compared to 0.96–0.99 in the original images, confirming effective spatial decorrelation. Differential cryptanalysis is addressed by the near-ideal NPCR and UACI values. Statistical attacks are mitigated by the near-uniform distribution of encrypted pixels. Known-plaintext attacks are countered by session-dependent chaotic key generation: even with one plaintext-ciphertext pair, key streams for subsequent sessions differ due to chaotic sensitivity. Figure 5 presents a radar-chart comparison across six security dimensions, confirming the framework's holistic security improvement.

7. Conclusion

This paper presented the Multilayer Visual Cryptography Framework (MLVCF), a novel three-layer encryption architecture that addresses the principal limitations of existing visual cryptography schemes—namely pixel expansion, contrast degradation, and insufficient cryptographic hardness. By integrating chaotic pixel permutation (logistic map), XOR-based probabilistic share generation, and Lorenz-system key-stream diffusion, the MLVCF delivers a cryptosystem with near-ideal randomness in the encrypted domain and near-lossless fidelity in the decrypted domain. Experimental results confirm that MLVCF outperforms five representative baseline methods across all evaluated metrics. A decryption PSNR of 38.6 dB and SSIM of 0.95, combined with NPCR and UACI values within 0.01% of theoretical ideals, demonstrate that the framework successfully bridges the gap between perceptual security and cryptographic rigor. The total key space exceeding 10^{223} provides a comfortable security margin against both classical and quantum adversaries. Future work will investigate extension of MLVCF to video data streams, integration of authenticated key exchange protocols for distributed multi-party scenarios, and hardware implementation on resource-constrained IoT devices. Formal verification of the security properties using automated theorem provers represents a valuable direction for establishing provable security guarantees.

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