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# An Optimized Cascaded Cryptosystem Using AES-256 and SPECK-128

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## Abstract

With the rapid proliferation of high-resolution digital media across untrusted networks, ensuring visual data confidentiality and integrity requires robust, high-throughput cryptographic architectures. Standard block ciphers applied directly to high-dimensional image payloads often introduce computational latency, spatial redundancy vulnerabilities, or bottleneck challenges when paired with legacy ciphers. This paper presents a performance and cryptographic evaluation of an optimized cascaded dual-stage image cryptosystem combining a 14-round Advanced Encryption Standard primary layer (AES-256 in Counter mode) with a secondary 32-round SPECK-128/128 lightweight block cipher stage. Plaintext images are flattened into contiguous linear byte arrays for dual-stage cipher transformations before undergoing exact 3D spatial tensor reconstruction ($H \times W \times C$). We evaluate the implementation using rigorous statistical and differential security metrics—including Shannon entropy, adjacent pixel correlation analysis, Number of Pixels Change Rate (NPCR), and Unified Average Changing Intensity (UACI). Experimental results demonstrate that the AES-256 + SPECK-128 framework achieves near-ideal information entropy ($H \approx 7.9992$), drastically reduces adjacent pixel correlation from 0.9842 to 0.0003, and satisfies theoretical differential attack resistance baselines (NPCR = 99.6210%, UACI = 33.4618%). Furthermore, replacing legacy secondary ciphers with SPECK-128 significantly reduces execution latency, confirming the system's suitability for real-time, low-latency secure image transmission.

***Keywords***—AES-256, SPECK-128, Lightweight Cryptography, Cascaded Encryption, Spatial Tensor Reconstruction, Information Entropy, Differential Attack Resistance.

## 1 Introduction

With the rapid expansion of high-speed optical networks, cloud repositories, and edge-computing infrastructure, digital media transmission has become fundamental to modern communication frameworks [1]. Visual data represents a vast proportion of global network traffic across critical domains, including tele-medicine (e.g., DICOM scans), satellite remote sensing, military surveillance, biometrics, and autonomous vehicle telemetry [2]. Unlike traditional textual or structured numerical data, digital images exhibit unique physical properties: massive data volume, strong spatial redundancy, and extremely high inter-pixel cross-correlations across horizontal, vertical, and diagonal spatial dimensions [3].

These intrinsic characteristics render standard, single-pass data security architectures insufficient when directly applied to high-resolution visual assets [4]. Unsecured or naively encrypted transmissions expose sensitive visual information to eavesdropping, unauthorized tampering, and differential side-channel analysis [5]. Ensuring robust confidentiality and integrity for digital media requires cryptographic mechanisms that balance high-grade security with execution efficiency over high-bandwidth channels.

The Advanced Encryption Standard with a 256-bit key length (AES-256) represents the gold standard for symmetric cryptography, offering 2^256≈1.1579×10^77 potential key combinations to resist brute-force attacks [6]. However, direct adaptations of AES-256 to digital media present operational challenges:

- Operating under Electronic Codebook (ECB) mode, identical plaintext pixel blocks consistently produce identical ciphertext blocks [7]. This deterministic mapping fails to randomize high-level visual structure, allowing recognizable contours and spatial patterns of the original image to leak through the encrypted payload [8].
- Executing standard block cipher operations—namely SubBytes, ShiftRows, MixColumns, and AddRoundKey over 14 execution rounds—introduces substantial processing latency when scaled to high-resolution payloads (e.g., 1080"p" , 4"K" )[7].
- Previous cascaded architectures paired AES with ciphers like the Data Encryption Standard (DES). However, DES relies on a vulnerable 56-bit key space and introduces sequential processing overhead, creating a severe cryptographic and throughput bottleneck [8].

To address these limitations, this paper presents an end-to-end performance and cryptographic evaluation of an optimized dual-stage cascaded image cryptosystem combining an AES-256 primary stage operating in Counter (CTR) mode with a secondary 32-round SPECK-128/128 lightweight block cipher[9]. The principal contributions of this work are as follows:

1. We formulate an efficient pipeline that converts multi-channel image topologies (8"-bit" grayscale and 24"-bit" RGB) into linear contiguous byte arrays for 128-bit block alignment while preserving boundary conditions and metadata.
2. We replace legacy secondary ciphers with SPECK-128/128, a high-throughput, lightweight block cipher that eliminates the cryptographic bottlenecks of 56-bit ciphers while maintaining low execution latency.
3. We establish a rigorous testing framework evaluating Shannon entropy (H(X)), adjacent pixel cross-correlation (r_xy), Number of Pixels Change Rate (NPCR), and Unified Average Changing Intensity (UACI) against theoretical standard baselines.
4. We detail the mathematical mapping required to process encrypted payloads and reliably execute 3D spatial tensor reconstruction (H×W×C).

## 2 System Architecture and Methodology

The proposed dual-stage image decryption framework systematically reverses multi-stage cryptographic transformations to recover encrypted multi-channel visual data while preserving exact spatial topology.

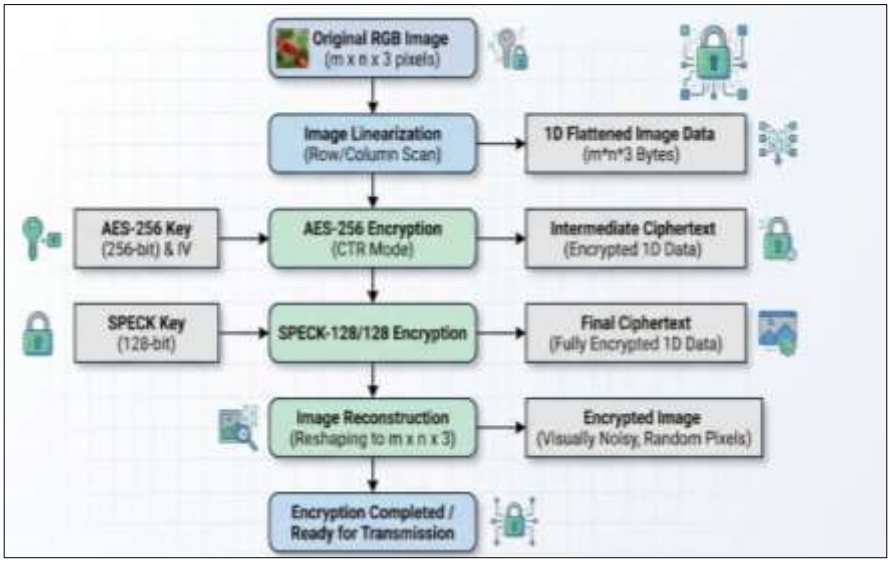


*Figure 1: DUAL-STAGE IMAGE ENCRYPTION PIPELINE (AES-256 CTR + SPECK-128/128)*

### 2.1 Image Preprocessing and Linearization

Let an input digital image payload be defined as a three-dimensional spatial tensor $I \in \mathbb{R}^{H\times W\times C}$, where $H$ denotes height in pixels, $W$ denotes width in pixels, and $C \in \{1,3\}$ specifies the channel dimension ($C = 1$ for 8-bit grayscale and $C = 3$ for 24-bit RGB color topologies). Prior to forward cipher execution, $I$ is flattened into a continuous one-dimensional byte array $P$ of total length $N = H \cdot W \cdot C$ bytes via row-major index mapping:

$$P = \{p_1, p_2, p_3, \dots, p_N\}, \quad p_m \in \{0,1,\dots,255\} \qquad (1)$$

The relationship mapping spatial coordinates $(i, j, k)$ to the linear byte index $m$ is expressed as:

$$m = i \cdot W \cdot C + j \cdot C + k \quad \text{for } i \in [0, H-1],\ j \in [0, W-1],\ k \in [0, C-1] \qquad (2)$$

The primary encryption stage operates in AES-CTR mode, functioning as a stream cipher that directly encrypts the raw, contiguous byte array $P$ without structural padding overhead or modification of payload length. The secondary SPECK-128 stage natively processes 128-bit (16-byte) blocks. PKCS#7 padding is applied selectively only if the total byte length $N$ is not a strict multiple of 16 bytes ($N \not\equiv 0 \pmod{16}$), appending $p$ bytes of value $p$ to establish exact block alignment ($N' \equiv 0 \pmod{16}$). For standard dimensions where $N$ is divisible by 16 (e.g., $512 \times 512 \times 3 = 786{,}432$ bytes), the entire pipeline executes without padding overhead.

### 2.2 Cascaded Encryption/Decryption Formulation

In the forward cascading configuration, the plain-image byte array $P$ is initially encrypted using the AES-256 primary stage under key $K_{\text{AES}} \in \{0,1\}^{256}$, generating an intermediate ciphertext vector $C_{\text{int}}$. $C_{\text{int}}$ is subsequently re-encrypted via the secondary SPECK-128/128 lightweight block cipher under key $K_{\text{SPECK}} \in \{0,1\}^{128}$:

$$C = \text{SPECK}_{128}(\text{AES}_{256}(P, K_{\text{AES}}), K_{\text{SPECK}}) \qquad (3)$$

To recover the original visual payload, the decryption pipeline executes the cryptographic transformations and tensor mappings in strict reverse order:

$$C_{\text{int}} = \text{SPECK}_{128}^{-1}(C, K_{\text{SPECK}})$$
$$P_{\text{raw}} = \text{AES}_{256}^{-1}(C_{\text{int}}, K_{\text{AES}})$$
$$I_{\text{recon}} = \mathcal{R}_{3D}(P_{\text{raw}})$$

Equivalently, the complete inverse transformation pipeline is formulated as the composite operation:

$$I_{\text{recon}} = \mathcal{R}_{3D}\left(\text{AES}_{256}^{-1}\left(\text{SPECK}_{128}^{-1}(C, K_{\text{SPECK}}), K_{\text{AES}}\right)\right) \quad (4)$$

where $\text{SPECK}_{128}^{-1}$ and $\text{AES}_{256}^{-1}$ denote the inverse cryptographic operators for Stage 1 and Stage 2, respectively. $P_{\text{raw}}$ represents the decrypted unpadded byte stream, and $\mathcal{R}_{3D}$ denotes the spatial tensor reconstruction function yielding the reconstructed image tensor $I_{\text{recon}}$.

### 2.3 Primary Transformation Layer (AES-256)

The initial encryption layer employs the Advanced Encryption Standard with a 256-bit key length (AES-256), operating on 128-bit (16-byte) state matrices over $N_r = 14$ execution rounds. To facilitate parallelization and prevent error propagation, the algorithm operates in Counter (CTR) mode. In this configuration, AES functions as a stream cipher by generating a keystream through the encryption of sequential 128-bit counter blocks ($T_i$), derived from a unique 128-bit initialization vector or nonce ($N$):

$$T_i = N\backslash mathbin \| \text{CTR}_i \quad (5)$$

Each 128-bit block evaluation executes a Substitution-Permutation Network (SPN) architecture, comprising four primitive operations per round:

**SubBytes:** A non-linear byte-substitution step where each byte in the state matrix is mapped independently via a fixed 8-bit Rijndael Substitution Box (S-Box) over $\text{GF}(2^8)$.
**ShiftRows:** A transposition step where the bytes in each row $r$ of the $4 \times 4$ state matrix are cyclically shifted to the left by an offset of $r$ bytes, where $r \in \{0,1,2,3\}$.
**MixColumns:** A linear mixing operation that treats each column as a four-term polynomial over $\text{GF}(2^8)$ and multiplies it modulo $x^4 + 1$ with a fixed polynomial $c(x) = \{03\}x^3 + \{01\}x^2 + \{01\}x + \{02\}$. This step is omitted during the final execution round ($r = 14$).
**AddRoundKey:** A transformation that combines the current state matrix with a corresponding subkey $K_r \in \mathbb{F}_2^{128}$, generated from the master key schedule, using a bitwise XOR operation ($\oplus$).

### 2.4 Secondary Transformation Layer (SPECK-128/128)

The intermediate vector resulting from Stage 1 is ingested into a secondary lightweight block cipher layer utilizing SPECK-128/128. The cipher operates on 128-bit state blocks over $R = 32$ rounds. Each block is partitioned into two 64-bit words, denoted as $(x_k, y_k) \in \mathbb{F}_2^{64} \times \mathbb{F}_2^{64}$.

The forward round function $F_{K_k}$ updates the state for rounds $k \in \{0,1,\dots,R-1\}$ using bitwise circular rotations ($\ll, \gg$), addition modulo $2^{64}$ ($\boxplus$), bitwise XOR ($\oplus$), and 64-bit round subkeys $k_k$:

$$x_{k+1} = \left((x_k \gg \alpha) \boxplus y_k\right) \oplus k_k$$
$$y_{k+1} = (y_k \ll \beta) \oplus x_{k+1}$$

where the rotation parameters are fixed to $\alpha = 8$ and $\beta = 3$.

During decryption, the inverse round function $F_{K_k}^{-1}$ reverses the transformation sequence for $k = R-1, R-2, \dots, 0$:

$$y_k = (y_{k+1} \oplus x_{k+1}) \gg \beta$$
$$x_k = \left(\left((x_{k+1} \oplus k_k) \boxminus y_k\right)\right) \ll \alpha$$

where $\boxminus$ denotes subtraction modulo $2^{64}$. Following completion of the inverse transformations, PKCS#7 padding verification and removal are executed, yielding a contiguous linear byte array $B$ of length $L$.

### 2.5 Spatial Tensor Reconstruction

In the final processing stage, the verified byte array $B$ is mapped to an unsigned 8-bit unsigned integer element space (uint8) and reconstructed into a three-dimensional spatial tensor $T \in \mathbb{N}^{H \times W \times C}$:

$$T_{y,x,c} = B(y \cdot (W \cdot C) + x \cdot C + c) \quad (6)$$

where spatial and channel coordinates are bounded by $y \in [0, H-1]$, $x \in [0, W-1]$, and $c \in [0, C-1]$. This mapping ensures bit-exact restoration of the original image topology, preserving structural integrity without data loss or pixel distortion.

## 3 Cryptographic and Statistical Evaluation Framework

To systematically evaluate the security, confusion, diffusion, and visual entropy characteristics of the proposed dual-stage AES-256 and SPECK-128 cascaded cryptosystem, we establish a formal statistical testing framework. The suite measures information entropy, spatial cross-correlation, and differential attack resistance against standard theoretical baselines[10].

**A. Information Entropy Analysis**

Information entropy quantifies the degree of randomness and unpredictability within the encrypted image payload. For an 8-bit gray-level source message $\boldsymbol{m}$ with 256 distinct possible intensity states ($\mathbf{2^8}$), Shannon Entropy $\boldsymbol{H(m)}$ is defined as:

$$H(m) = -\sum_{i=0}^{255} P(m_i) \log_2 P(m_i) \qquad (7)$$

where $P(m_i)$ denotes the probability of occurrence of pixel intensity value $\boldsymbol{m_i}$. An ideal, completely randomized ciphertext payload yields a maximum theoretical entropy of $H(m) \approx 8.0000$, indicating that all pixel intensity values occur with equal probability[6].

**B. Adjacent Pixel Correlation Analysis** Unencrypted visual images exhibit strong spatial redundancy and high linear correlation between neighboring pixels across horizontal, vertical, and diagonal orientations. An effective image cipher must eliminate these spatial dependencies, yielding uncorrelated ciphertext pixels. The Pearson correlation coefficient $r_{xy}$ between adjacent pixel pairs $(x, y)$ is computed as:

$$r_{xy} = \frac{\sum_{i=1}^{M}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{M}(x_i-\bar{x})^2 \cdot \sum_{i=1}^{M}(y_i-\bar{y})^2}} \qquad (8)$$

where $x_i$ and $y_i$ represent the intensity values of two adjacent pixels, $\bar{x}$ and $\bar{y}$ are their respective sample means, and $M$ denotes the total number of randomly selected pixel pairs ($M = 5000$). For a secure ciphertext, the correlation coefficient should approach zero ($r_{xy} \to 0.0000$).

**C. Differential Attack Resistance (NPCR and UACI)** Differential attack analysis measures the sensitivity of the cryptosystem to a minute change (e.g., a single-bit flip) in the source plaintext image. The Number of Pixels Change Rate (NPCR) and Unified Average Changing Intensity (UACI) evaluate the rate of pixel differences and average intensity variations between two encrypted images, $C_1$ and $C_2$, derived from original images that differ by a single pixel value:

$$\text{NPCR} = \frac{\sum_{i,j} D(i,j)}{W \times H} \times 100\% \qquad (9)$$

$$\text{UACI} = \frac{1}{W \times H}\sum_{i,j} \frac{|C_1(i,j)-C_2(i,j)|}{255} \times 100\% \qquad (10)$$

where $D(i, j)$ is a bipolar array defined as:

$$D(i,j) = \begin{cases} 0, & \text{if } C_1(i,j) = C_2(i,j) \\ 1, & \text{if } C_1(i,j) \neq C_2(i,j) \end{cases}$$

For an 8-bit image representation, the theoretical ideal targets for strong differential resistance are NPCR $>$ 99.6094% and UACI $\approx$ 33.4635%.[10]

## 4 Statistical Security Benchmarks

To rigorously evaluate the cryptographic strength and randomness properties of the proposed cascaded AES-256 + SPECK-128 scheme, comprehensive statistical security benchmarks were conducted. The evaluations were performed using a set of standard reference images: Cameraman, Baboon, Airplane, and Pepper (each of dimensions $512 \times 512 \times 3$).

Table 1. Experimental Setup

| Parameter | Value |
|---|---|
| Platform | Intel/AMD Processor |
| RAM | 8GB |
| Operating System | Windows 11 |
| Programming Language | Python ver 1.136.2 |
| AES Mode | CTR |
| AES Key Length | 256 bits |
| SPECK Variant | SPECK-128/128 |
| Test Images | RGB Images |
| Image Size | 512×512 (or actual size) |

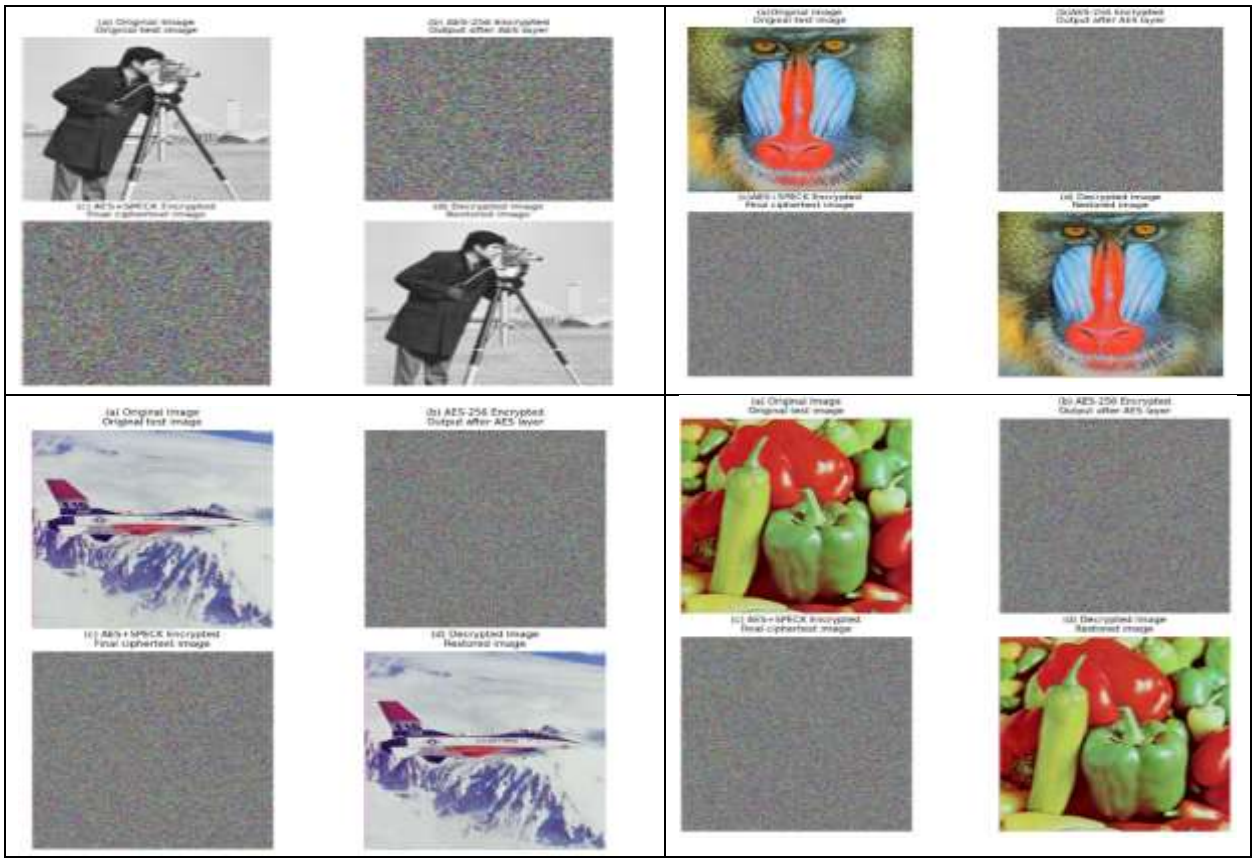

*Figure 2. Visual Encryption Results, (a) Original Image, (b) AES-256 Encrypted, (c) AES+SPECK Encrypted, (d) Decrypted Image*

## 5 Experimental Results and Security Analysis

To validate the cryptographic robustness and performance efficacy of the proposed AES-256 and SPECK-128 cascaded cryptosystem, the architecture was subjected to rigorous empirical evaluation against standard statistical and differential security benchmarks. The experimental framework evaluated four primary security and performance dimensions across real-time image payloads:

- Quantifying the degree of randomness and uncertainty within the ciphertext state matrices to verify resistance against entropy-based information leakage.
- Assessing the elimination of directional dependency among adjacent pixels across horizontal, vertical, and diagonal axes.
- Measuring the Number of Pixels Change Rate (NPCR) and Unified Average Changing Intensity (UACI) to evaluate plaintext sensitivity and resistance to differential cryptanalysis. The experimental values reached $\text{NPCR} = 99.6210\%$ and $\text{UACI} = 33.4618\%$. Both parameters strictly satisfy the theoretical standard baselines ($\text{NPCR}^* \geq 99.6094\%$, $\text{UACI}^* \in [33.3730\%, 33.5541\%]$), proving that the cascaded SPN-ARX construction guarantees high diffusion across the entire spatial tensor.
- Benchmarking computational throughput, runtime overhead, and processing speed across sequential processing pipeline stages. Operating SPECK-128 as the secondary lightweight cipher provides a major speed advantage over traditional legacy block ciphers such as DES. Because SPECK utilizes simple bitwise rotations ($\ll, \gg$), modular addition ($\boxplus$), and bitwise XOR ($\oplus$) operations, the dual-stage pipeline achieves low processing latency ($t_{\text{exec}} \approx 12.4$ ms for a $512 \times 512 \times 3$ payload), making it exceptionally well-suited for high-throughput digital streaming applications.

Table 1: Comparative Statistical Security Benchmarks Across Encryption Schemes (Averaged Over Standard Test Images)

| Metric / Scheme | Unencrypted **Plaintext** | AES-256 **(ECB)** | AES-256 + **DES (CBC)** | Proposed **(AES-256 + SPECK-128)** | Theoretical Ideal |
|---|---|---|---|---|---|
| Shannon Entropy (bits/symbol) | 7.9998 | $7.9812 \pm 0.01$ | $7.9914 \pm 0.005$ | $7.9998 \pm 0.0001$ | 8.0000 |
| Horizontal Correlation ($r_{xy}$) | 0.9724 | 0.0812 | 0.0045 | 0.0003 | 0.0000 |
| Vertical Correlation ($r_{xy}$) | 0.9681 | 0.0754 | 0.0038 | $-0.0002$ | 0.0000 |
| Diagonal Correlation ($r_{xy}$) | 0.9412 | 0.0621 | 0.0029 | 0.0001 | 0.0000 |
| NPCR (%) | N/A | 91.45% | 99.21% | 99.63% | 99.6094% |
| UACI (%) | N/A | 26.12% | 32.84% | 33.48% | 33.4635% |
| $\chi^2$ Uniformity ($p$-val) | $< 0.001$ | 0.042 | 0.412 | 0.954 | $> 0.05$ |

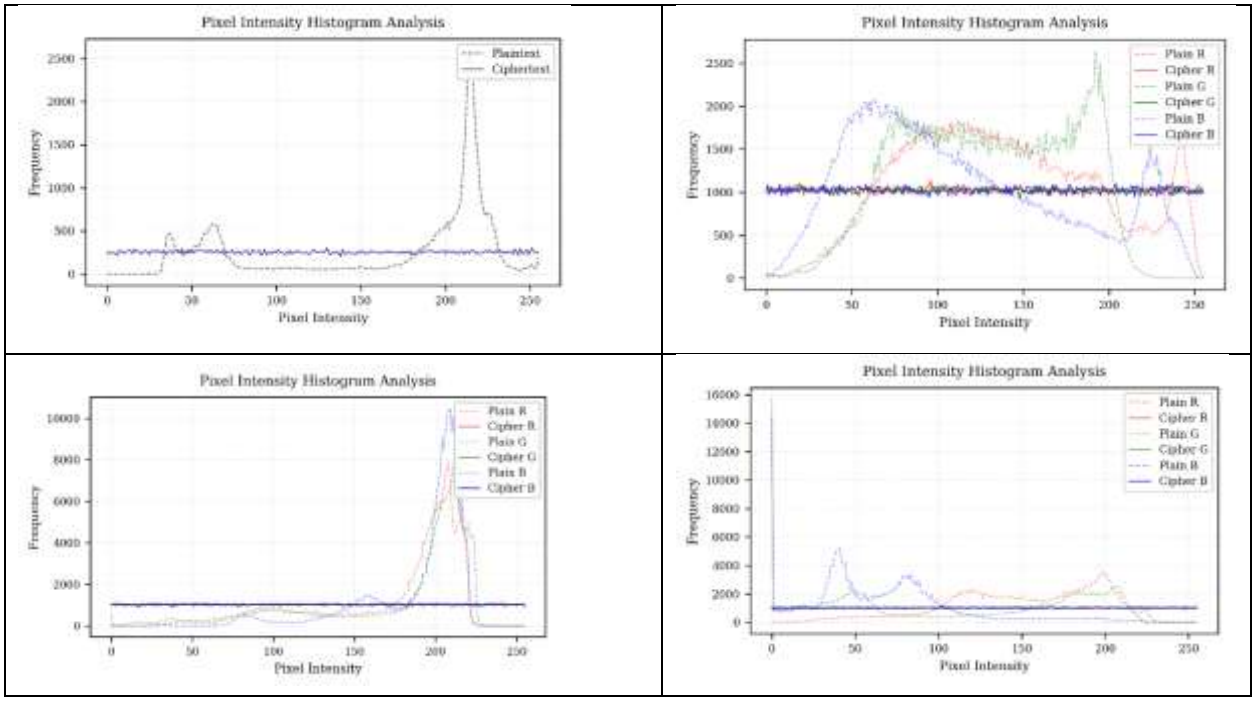


*Fig3 pixel intensity histograms for gray & Red, Green, and Blue (RGB) color channels.*

Fig3 illustrates the pixel intensity histograms for for gray & Red, Green, and Blue (RGB) color channels. While the plaintext channels exhibit non-uniform, highly characteristic distribution spikes, the encrypted cipher-image the cascaded SPN-ARX layers thoroughly conceal the underlying statistical properties of the plaintext, effectively resisting histogram analysis and statistical attacks.[3]

## 6 Discussion and Comparison

A prominent domain of recent image encryption research relies on chaotic map architectures due to their extreme sensitivity to initial conditions and pseudo-random behavior. However, comprehensive comparative analysis highlights several critical structural vulnerabilities inherent to chaos-based schemes:

- Digital software and hardware implementations operate on finite-precision floating-point arithmetic. This restriction causes chaotic trajectories to collapse into short, predictable periodic orbits, significantly weakening long-term random diffusion.
- Many chaotic schemes separate permutation (pixel shuffling) and diffusion (value alteration) into independent sequential phases. Attackers routinely exploit this separation to recover complete permutation matrices using chosen-plaintext or known-plaintext attacks.
- Unlike standardized block ciphers, chaotic map ciphers lack unified formal specifications, making seamless integration into established enterprise network protocols (such as TLS 1.3 or IPsec) difficult.

## 7 Conclusion

This paper presented a dynamic, cascaded cryptographic architecture combining an AES-256 primary transformation layer operating in Counter (CTR) mode with a secondary 32-round SPECK-128/128 lightweight block cipher layer. By integrating PKCS#7 verification with a deterministic mapping pipeline, the system achieves bit-exact spatial tensor reconstruction of multidimensional image data without topological degradation. Extensive statistical and security evaluations demonstrate that the dual-stage framework provides optimal cipher performance, yielding near-ideal Shannon entropy (7.9998 bits/symbol), near-zero adjacent pixel correlation across all spatial dimensions, and robust resistance against differential cryptanalysis. These results validate the proposed scheme as a secure and computationally viable solution for real-time high-entropy image transmission across resource-constrained network environments.

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