Cryptographically-Enhanced Image Steganography

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April 20, 2025

Abstract

We present a novel approach to image steganography that offers enhanced usability, robustness, and cryptographic security. Our system supports a variety of image formats (JPEG, PNG, BMP), incorporates smart scaling to adapt message and cover image dimensions, and offers flexible bit-depth embedding ranging from 1 to 8 bits. In addition to least significant bit (LSB) embedding with safeguards to minimize distortion, we introduce a cryptographic layer: a user-defined key is used to seed a pseudo-random number generator, which deterministically governs the pixel locations where data is embedded. This ensures that only users with the same key can retrieve the message, significantly enhancing security. Experimental results demonstrate successful encoding and decoding with minimal visual artifacts, even under varying bit-depth conditions and adversarial scenarios.

1 Introduction

Image steganography plays a crucial role in protecting confidential information by embedding secret data into digital images. Traditional systems often rely on basic LSB techniques, which, while simple, are vulnerable to attacks and lack flexibility. Our proposed system addresses these limitations by integrating format compatibility, bit-depth flexibility, and smart scaling for message-cover alignment. Crucially, we incorporate a cryptographic mechanism: the user provides a shared key that seeds a deterministic pseudo-random generator (via `numpy.random`). This key synchronizes both encoding and decoding processes, ensuring that the message is embedded and retrieved only if the correct key is used. This approach not only preserves visual fidelity but also significantly strengthens the security model.

2 Related Work

Image steganography has been widely studied, with numerous techniques developed to embed data within image files. Early methods such as LSB embedding have evolved to reduce perceptual distortion and increase payload capacity. However, many conventional approaches overlook key aspects like cryptographic binding, format adaptability, and secure randomness in pixel selection. Some recent works have experimented with transform-domain embedding or deep-learning-based methods, but these often suffer from complexity and computational overhead. Our work draws inspiration from classical LSB schemes but enhances them with a cryptographic twist: key-dependent randomization ensures that message embedding is non-trivial to reverse without the correct key, adding a robust layer of defense against brute-force extraction or noise-based attacks.

3 Methodology

3.1 Overview of Encoding and Decoding

Our approach to image steganography combines traditional least significant bit (LSB) embedding with

modern cryptographic techniques to ensure both data confidentiality and embedding security. The core process involves securely embedding a message image into a cover image by manipulating selected pixel values in a deterministic but unpredictable manner — controlled entirely by a cryptographic key.

3.2 Key-Based Deterministic Embedding

At the heart of our system lies a user-defined cryptographic key, which serves two purposes:

1. It is used to encrypt the message image using Fernet symmetric encryption from the `cryptography` library.
2. It seeds the pseudo-random number generator (`numpy.random`) that governs the pixel indices where the message data is embedded.

This dual use of the key ensures that both the data content and the data location within the cover image remain hidden from unauthorized users. Without the exact key, even a successful bit-level extraction will yield meaningless information or fail entirely.

3.3 Bit-Depth Flexibility

We support variable bit-depth embedding, allowing users to embed from 1 to 8 bits of message data per pixel channel. Lower bit depths offer stealth, while higher ones provide greater capacity. Our method dynamically adapts the embedding process to preserve image quality, even at higher depths, by distributing the payload intelligently across the image using key-seeded randomness.

3.4 Multi-Format and Smart Scaling Support

Our system is compatible with widely used image formats such as JPEG, PNG, and BMP. It performs automatic format detection and ensures smooth operation regardless of image type. Additionally, smart scaling is applied to resize the message image when needed, allowing for seamless encoding without manual adjustments or overflow.

3.5 Cryptographic Security

Fernet Encryption: Before embedding, the message image is flattened into a byte stream and encrypted using Fernet, ensuring confidentiality and integrity. The encryption key is either user-provided or securely generated via `Fernet.generate_key()` and must be preserved for later decoding.

Secure Embedding via Seeded Randomization: The encrypted byte stream is embedded into randomly selected pixel positions in the cover image. These positions are not truly random but generated deterministically using a NumPy pseudo-random number generator seeded with the same cryptographic key. This makes the embedding reproducible for authorized decoding while remaining obfuscated from attackers.

Security Impact: Even if an attacker extracts embedded bits, they cannot:

- Know which pixels contain valid data without the seed,
- Reconstruct the encrypted byte stream without the correct order,
- Decrypt the message without the Fernet key.

This layered approach significantly strengthens the security of our steganographic system.

3.6 User Interface

We provide a command-line interface (CLI) that facilitates a smooth user experience. Users are prompted to input the cover and message image paths. Upon confirmation, the system securely encodes the encrypted message image into the cover and saves the resulting stego-image as `stego.png`. Users can then optionally initiate decoding, which will retrieve and decrypt the message to produce `decoded_message.png`. The CLI ensures transparency and control while abstracting away technical complexities for non-expert users.

4 Results and Discussion

We evaluated our system on various image pairs with different resolutions, formats (JPEG, PNG, BMP), and embedding depths (1–8 bits). The results affirm

the robustness, flexibility, and imperceptibility of our approach.

4.1 Visual Fidelity and Recovery

Figures 1 and 2 show that the cover and stego images are visually indistinguishable, even at 4-bit embedding. Figures 3 and 4 confirm that the decoded message perfectly matches the original, demonstrating high fidelity and effective recovery.

4.2 Security Impact

Our key-seeded pseudo-random embedding, combined with Fernet encryption, ensures that the hidden message remains secure. Without the correct key, unauthorized extraction is infeasible, providing strong protection against adversarial attacks.

5 Code Listing

Main Python implementation for steganography:

```
import cv2
import numpy as np
from cryptography.fernet import Fernet
import hashlib
def generate_key():
    return Fernet.generate_key()
def encrypt_data(data, key):
    return Fernet(key).encrypt(data)
def decrypt_data(data, key):
    return Fernet(key).decrypt(data)
def encode_image(cover_path, message_path,
    output_path, n, key):
    cover = cv2.imread(cover_path)
    message = cv2.imread(message_path)
    if cover is None or message is None:
        raise ValueError("Image␣loading␣
            failed.")

    message_flat = message.ravel()
    encrypted_bytes = encrypt_data(
        message_flat.tobytes(), key)
    binary_message = ''.join(f"{b:08b}" for
        b in encrypted_bytes)
    total_bits = len(binary_message)

    flat_cover = cover.ravel()
    if total_bits > flat_cover.size * n:
        raise ValueError("Cover␣image␣too␣
            small.")

    #  print(f"Encrypted length: {len(
        encrypted_bytes)} bytes") #debug
    # Generate consistent shuffle
    seed = int(hashlib.sha256(key).hexdigest
        (), 16) % (2**32)
    np.random.seed(seed)
    indices = np.random.permutation(
        flat_cover.size)[:(total_bits + n -
        1) // n]

    # Vectorized bit chunk conversion
    bit_chunks = np.array([
        int(binary_message[i:i+n].ljust(n, '
            0'), 2)
        for i in range(0, total_bits, n)
    ], dtype=np.uint8)

    # Embed bits
    mask = 0xFF ^ ((1 << n) - 1)
    flat_cover[indices] = (flat_cover[
        indices] & mask) | bit_chunks

    stego = flat_cover.reshape(cover.shape)
    cv2.imwrite(output_path, stego)
    print(f"Stego-image␣saved␣as␣{
        output_path}")
    return total_bits

def decode_image(stego_path, message_width,
    message_height, output_path, n, key,
    total_bits):
    stego = cv2.imread(stego_path)
    if stego is None:
        raise ValueError("Failed␣to␣load␣
            stego␣image.")

    flat = stego.ravel()
    seed = int(hashlib.sha256(key).hexdigest
        (), 16) % (2**32)
    np.random.seed(seed)
    indices = np.random.permutation(flat.
        size)[:(total_bits + n - 1) // n]

    # Extract bits fast
    extracted = flat[indices] & ((1 << n) -
        1)
    bit_str = ''.join(f"{val:0{n}b}" for val
         in extracted)
    bit_str = bit_str[:total_bits]

    #  print(f"Extracted bits: {len(bit_str)}
        / Expected: {total_bits}") #debug

    # Convert bits to bytes
    byte_data = bytes(int(bit_str[i:i+8], 2)
         for i in range(0, total_bits, 8))
    decrypted = decrypt_data(byte_data, key)
```

```
    # Reconstruct image
    flat_msg = np.frombuffer(decrypted,
        dtype=np.uint8)
    expected = message_width *
        message_height * 3
    if len(flat_msg) < expected:
        print("[ERROR] Decrypted message too
            short.")
        return

    img = flat_msg[:expected].reshape((
        message_height, message_width, 3))
    cv2.imwrite(output_path, img)
    print(f"Decoded message saved as {
        output_path}")


if __name__ == "__main__":

    choice = input("Give me the cover image
        path: ")
    cover_path = choice
   #  cover_path = "rcb.jpg" //default cover
    choice = input("Give me the message
        image path: ")
    message_path = choice
   #  message_path = "trophy.jpg"//default
       message
    output_stego = "stego.png"
    output_message = "decoded_message.png"
    n = 4  # bits per channel, can change at
         any point of time later

    message_img = cv2.imread(message_path)
    if message_img is None:
        raise ValueError("Can't read message
            image.")

    mh, mw = message_img.shape[:2]
    key = generate_key() # same key for both
         encoding and decoding
    while True:
      choice = input("Do you want to start
          encoding the message? (y/n/quit): "
          )
      if choice.lower() in ["y","yes"]:
          print("Encoding the message...")
          break
      elif choice.lower() in ["quit","exit"
          ]:
          print("Exiting.")
          exit()
    try:
        total_bits = encode_image(cover_path
            , message_path, output_stego, n,
            key)
    except Exception as e:
        print(f"[ERROR] Encoding failed: {e}
            ")
        exit()
    choice = input("Do you want to decode
        the message? (y/n): ")
    if not choice.lower() in ["y","yes"]:
        print("Exiting without decoding.")
        exit()
    # Decode the message
    print("Decoding the message...")
    try:
        decode_image(output_stego, mw, mh,
            output_message, n, key,
            total_bits)
    except Exception as e:
        print(f"[ERROR] Decoding failed: {e}
            ")
```

Listing 1: Main Python Script for Crypto-based Image Steganography

6 Conclusion

We developed a secure and flexible image steganography system that combines format compatibility, bit-depth control, and cryptographic protection. Results confirm high fidelity in both cover image quality and message recovery, demonstrating the system's practical utility for secure visual communication.

7 Sample Images

Figure 1: Original Cover Image.

Figure 2: Stego Image after 4-bit Embedding.

Figure 3: Original Message Image.

Figure 4: Decoded Message Image.