Multi-Image Steganography Security System: A Hybrid Approach Combining LSB Embedding and Fernet Encryption

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Abstract

The proliferation of digital communication has intensified the need for robust methods to protect sensitive information from unauthorized access. This paper presents a Multi-Image Steganography Security System that combines cryptographic encryption with image-based data hiding to achieve dual-layer security. The proposed system encrypts arbitrary files using the Fernet symmetric encryption scheme, which implements AES-128 in CBC mode with HMAC-based authentication, ensuring both confidentiality and integrity of the payload. The encrypted data is subsequently distributed across multiple carrier images using Least Significant Bit (LSB) steganography, where individual bits of the ciphertext replace the least significant bits of pixel values, rendering the modifications imperceptible to human observation.

The system architecture addresses several limitations inherent in single-image steganography approaches. By distributing the payload across multiple images, the system increases embedding capacity proportionally with the number of carrier images, accommodates larger files without degrading individual image quality, and complicates steganalysis efforts by fragmenting the hidden data. The implementation leverages Python's ecosystem, utilizing the Pillow library for image manipulation, NumPy for efficient array operations, the cryptography library for secure encryption, and Tkinter for an accessible graphical user interface.

The embedding process begins with reading the target file in binary mode, encrypting it using a locally stored Fernet key, converting the ciphertext to a binary string representation, and distributing these bits across the flattened pixel arrays of selected carrier images. Each pixel's least significant bit is conditionally modified to encode one bit of the encrypted payload. The modified arrays are reconstructed into images and saved with preserved format integrity. Extraction reverses this process by collecting LSB values from each carrier image, reconstructing the binary stream, converting to bytes, and decrypting using the same Fernet key.

Experimental observations confirm that the visual quality of carrier images remains virtually unchanged after embedding, as modifications occur only in the least perceptually significant bit plane. The system successfully handles various file types including text documents, compressed archives, and binary executables, demonstrating format-agnostic capability. Security analysis indicates that without access to the encryption key, intercepted carrier images reveal no meaningful information about the hidden payload, while the distributed nature of embedding across multiple images provides additional obscurity.

The practical utility of this system extends to secure document transmission, covert communication channels, digital watermarking applications, and educational

demonstrations of steganographic principles. The graphical interface enables users without technical expertise to embed and extract hidden files through intuitive button-based interactions. Future enhancements could incorporate adaptive embedding algorithms that select optimal pixel locations based on image characteristics, support for additional carrier formats including audio and video, and integration of asymmetric cryptography for key exchange scenarios.

Keywords

Steganography, Least Significant Bit (LSB), Fernet Encryption, Multi-Image Data Hiding, Information Security, Data Concealment, Cryptography, Image Processing, Python, Digital Forensics

Introduction

The digital age has fundamentally transformed how information is created, stored, and transmitted, bringing unprecedented convenience alongside equally unprecedented security challenges. Organizations and individuals routinely exchange sensitive data across networks that remain vulnerable to interception, surveillance, and unauthorized access. Traditional encryption methods address confidentiality by rendering data unreadable without the correct decryption key, yet encrypted communications inherently attract attention—the presence of ciphertext signals that something valuable warrants protection, potentially inviting targeted attacks or legal scrutiny in jurisdictions where encryption faces restrictions.

Steganography offers a complementary approach by concealing the very existence of secret communication. Derived from Greek roots meaning "covered writing," steganography embeds hidden messages within innocuous carrier media such that observers remain unaware any covert transmission has occurred. Unlike cryptography, which protects message content while revealing its presence, steganography protects against detection itself. When combined, these techniques create defense-in-depth: even if an adversary suspects hidden content and extracts the embedded data, encryption ensures the payload remains unintelligible without the decryption key.

Digital images provide particularly suitable carriers for steganographic embedding due to their ubiquity in modern communication, tolerance for minor modifications without perceptible quality degradation, and substantial data capacity. A single 24-bit color image contains three color channels per pixel, each represented by eight bits, yielding significant embedding potential when utilizing the least significant bit plane. Human visual perception exhibits limited sensitivity to small changes in pixel intensity, enabling modifications that remain invisible during casual inspection while encoding meaningful information.

This paper presents a Multi-Image Steganography Security System that advances conventional single-image approaches by distributing encrypted payloads across multiple carrier images. This architecture provides several advantages: increased total embedding capacity without proportionally degrading individual carrier quality, enhanced resistance to statistical steganalysis through payload fragmentation, and practical accommodation of larger files that might exceed single-image capacity constraints. The system implements Fernet encryption, a high-level symmetric

encryption recipe that provides authenticated encryption using AES-128-CBC with PKCS7 padding and HMAC-SHA256 message authentication, preventing both unauthorized decryption and undetected tampering.

The implementation utilizes Python for its extensive library ecosystem and rapid development capabilities. The graphical user interface built with Tkinter enables accessible interaction for users without command-line proficiency, supporting straightforward image selection, file designation, embedding execution, and extraction operations. The system generates and locally stores encryption keys automatically, manages output directories, and provides status feedback throughout operations. This combination of strong cryptography, effective steganography, and usable interface design creates a practical tool for secure covert communication applicable across educational, research, and operational contexts.

Literature Survey

Steganographic research has evolved substantially since its digital inception, with investigators proposing diverse embedding strategies optimized for various carrier media and security objectives. Fridrich et al. established foundational work on LSB embedding and replacement, demonstrating both its effectiveness for data hiding and its vulnerability to statistical detection methods that analyze histogram anomalies introduced by systematic bit replacement. Their research motivated development of more sophisticated embedding schemes that better preserve statistical properties of carrier images.

Westfeld and Pfitzmann introduced the F5 algorithm, which employs matrix encoding to improve embedding efficiency, reducing the number of pixel modifications required to encode a given payload. This approach decreases detectability by minimizing disturbance to carrier statistics. Subsequent work by Crandall formalized the relationship between code design and embedding efficiency, establishing theoretical frameworks for optimal embedding codes.

Pevný, Filler, and Fridrich proposed the HUGO algorithm (Highly Undetectable Steganography), which selects embedding locations based on local image complexity, preferentially modifying pixels in textured regions where changes prove least detectable. This content-adaptive approach significantly outperformed location-agnostic methods against trained steganalysis classifiers, demonstrating the importance of considering image characteristics during embedding.

Research into multi-image steganography remains comparatively limited but has attracted growing interest. Liao et al. explored distributed embedding across image sets to increase capacity and complicate detection, finding that spreading payloads thin across numerous carriers reduced per-image statistical disturbance. Zhang and Wang investigated secret sharing schemes combined with steganography, where payload reconstruction requires a threshold number of carrier images, providing both capacity scaling and recovery tolerance.

The intersection of cryptography and steganography has received attention as researchers recognized the complementary strengths of each approach. Subhedar and Mankar surveyed hybrid systems combining encryption with various steganographic

methods, concluding that dual-layer approaches provide meaningful security improvements over either technique alone. Kumar and Roopa examined AES encryption combined with LSB embedding, reporting successful concealment of encrypted data without perceptible carrier degradation.

Machine learning has increasingly influenced both steganographic embedding and steganalysis. Boroumand et al. developed deep learning classifiers capable of detecting steganographic content across multiple embedding algorithms, demonstrating that neural networks could learn relevant statistical features automatically. This advancement pressures embedding methods toward greater sophistication, motivating research into adversarial approaches that optimize embedding against detector models.

Recent work has explored steganography in emerging media types including deep neural network parameters, blockchain transactions, and social media content. Yang et al. demonstrated embedding within neural network weights, creating steganographic models that function normally while concealing hidden payloads. These developments suggest ongoing relevance for steganographic research as communication media continue evolving.

Existing System

Conventional steganography systems typically employ single-image embedding, where the entire payload is hidden within one carrier image. This approach faces inherent capacity limitations determined by carrier dimensions and color depth—exceeding these limits either fails outright or introduces unacceptable statistical distortions that facilitate detection. Single-image systems also concentrate risk, as compromise of the single carrier exposes the entire hidden message.

Most existing tools implement basic LSB replacement without preprocessing the payload, leaving hidden data vulnerable to extraction attempts even by unsophisticated adversaries who simply read LSB values systematically. While some systems incorporate password protection, many employ weak or proprietary schemes rather than established cryptographic standards, providing false security that may collapse under informed attack.

Current graphical tools often restrict supported file types, accepting only text messages or specific formats rather than arbitrary binary data. This limitation reduces practical applicability for users needing to conceal diverse content types. Additionally, many implementations lack proper error handling, failing ungracefully when users provide unsupported images or when embedded data exceeds carrier capacity.

Existing systems frequently expose encryption keys through insecure storage mechanisms or require users to manually manage key material, introducing operational complexity that non-technical users find burdensome. The absence of authenticated encryption in some implementations means that tampered carrier images may produce corrupted outputs without detection, potentially delivering maliciously modified content to recipients.

Proposed System

The proposed Multi-Image Steganography Security System addresses identified limitations through several architectural decisions. First, payload distribution across multiple carrier images scales embedding capacity linearly with carrier count, accommodating larger files without concentrating modifications in single images. This distribution also fragments the encrypted payload, meaning individual carrier analysis reveals only partial ciphertext of no independent value.

Second, the system employs Fernet encryption, which provides authenticated encryption through established cryptographic primitives. Fernet generates keys containing both encryption and authentication components, applies AES-128-CBC for confidentiality, and computes HMAC-SHA256 over the ciphertext to detect any tampering. This construction ensures that modified carrier images produce authentication failures during extraction rather than silent corruption.

Third, the implementation accepts arbitrary binary files for embedding, converting raw bytes to binary representation after encryption. This format-agnostic approach accommodates text documents, compressed archives, executable programs, and any other file type without modification.

Fourth, the graphical interface provides accessible operation for users without technical backgrounds. Button-based interactions for image selection, file selection, embedding, and extraction require no command-line knowledge. Status feedback keeps users informed of system state throughout operations.

Fifth, automatic key management generates and stores encryption keys transparently, eliminating manual key handling while ensuring keys remain available for extraction operations. The system creates necessary output directories automatically, reducing setup requirements.

Implementation

The implementation comprises five functional modules: encryption handling, bit conversion, embedding logic, extraction logic, and graphical interface.

The encryption module utilizes the cryptography library's Fernet class, which implements authenticated symmetric encryption. The generate_key() function creates a new Fernet key and persists it to a local file, executing only during initial system use. The load_key() function retrieves the stored key for subsequent operations. The encrypt() function accepts raw bytes and returns authenticated ciphertext, while decrypt() reverses this transformation, raising exceptions if authentication fails due to tampering or incorrect keys.

Bit conversion functions transform between byte sequences and binary string representations. The to_bits() function iterates through each byte, formatting it as an eight-character binary string with leading zeros preserved, then concatenates these strings. The from_bits() function reverses this process, parsing eight-bit chunks and converting each to its integer byte value, returning a bytes object.

The embedding module's embed_data() function orchestrates the hiding process. It reads the target file in binary mode, encrypts the contents, and converts the ciphertext to binary representation. The function calculates chunk sizes for distributing bits across carrier images, then iterates through each image. For each carrier, it opens the image using Pillow, converts to a NumPy array for efficient manipulation, and flattens the multidimensional array to a one-dimensional sequence. The function then iterates through pixel values, replacing each least significant bit with the corresponding payload bit by masking off the LSB with bitwise AND against the complement of 1, then OR-ing the payload bit. After processing, the array is reshaped to original dimensions, converted back to an image, and saved with a prefixed filename to the output directory.

The extraction module's extract_data() function reverses embedding. It iterates through carrier images, opens each, converts to a flattened NumPy array, and extracts LSB values by bitwise AND with 1. These bits are concatenated into a string across all carriers. The function converts the binary string to bytes, decrypts using the stored key, and writes the recovered plaintext to the user-specified output file.

The graphical interface creates a Tkinter window with buttons invoking each operation. Global variables track selected images and files across function calls. File dialogs enable intuitive selection, and message boxes provide completion feedback.

Algorithms

Fernet Encryption Algorithm

Fernet implements authenticated encryption using established primitives. Key generation produces 32 random bytes: 16 bytes for AES encryption and 16 bytes for HMAC authentication. Encryption prepends a version byte and timestamp, generates a random 16-byte initialization vector, pads the plaintext using PKCS7 to reach a multiple of the 16-byte block size, encrypts using AES-128 in CBC mode, computes HMAC-SHA256 over the version, timestamp, IV, and ciphertext, then concatenates all components and base64-encodes the result. Decryption reverses these steps, verifying the HMAC before attempting decryption to detect tampering.

LSB Embedding Algorithm

The embedding process follows these steps:

1. Read the target file as a byte sequence
2. Encrypt bytes using Fernet, producing ciphertext
3. Convert ciphertext to binary string representation
4. For each carrier image:
1. Load image and convert to NumPy array
2. Flatten array to one-dimensional pixel sequence
3. For each pixel, replace LSB with next payload bit
4. Reshape array and save modified image

LSB Extraction Algorithm

The extraction process follows these steps:

1. Initialize empty bit string
2. For each carrier image:
    1. Load image and convert to flattened NumPy array
    2. Extract LSB from each pixel, appending to bit string
3. Convert bit string to byte sequence
4. Decrypt bytes using Fernet, producing original plaintext
5. Write plaintext to output file

System Design

The system architecture follows a layered design separating concerns across distinct functional modules.

Presentation Layer

The Tkinter-based graphical interface provides user interaction capabilities. The main window contains four action buttons (Select Images, Select File to Hide, Embed, Extract) and a status label displaying current system state. Button callbacks invoke functions in lower layers, while message boxes communicate operation outcomes. The interface maintains minimal state through global variables tracking user selections.

Business Logic Layer

Core steganographic and cryptographic operations reside in this layer. The embedding logic coordinates file reading, encryption invocation, bit conversion, and iterative image processing. The extraction logic coordinates bit collection, byte conversion, decryption invocation, and file writing. This layer enforces operational sequencing and handles data transformation between formats.

Cryptographic Services Layer

The encryption module encapsulates all cryptographic operations behind a simple interface. Key management functions handle generation and retrieval transparently. Encryption and decryption functions accept and return byte sequences, hiding implementation details from calling code. This encapsulation facilitates potential future substitution of alternative cryptographic schemes.

Data Access Layer

File operations for reading input files, writing output images, and storing encryption keys reside in this layer. The PIL library handles image format parsing and encoding. NumPy provides efficient array manipulation for pixel-level operations. Standard file I/O manages binary data transfer.

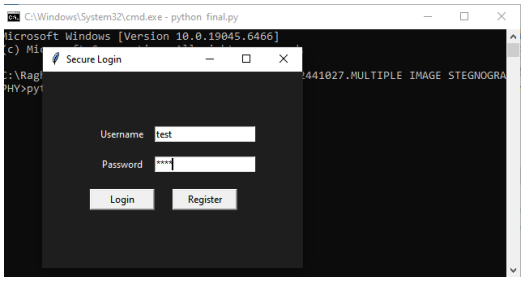
Data Flow

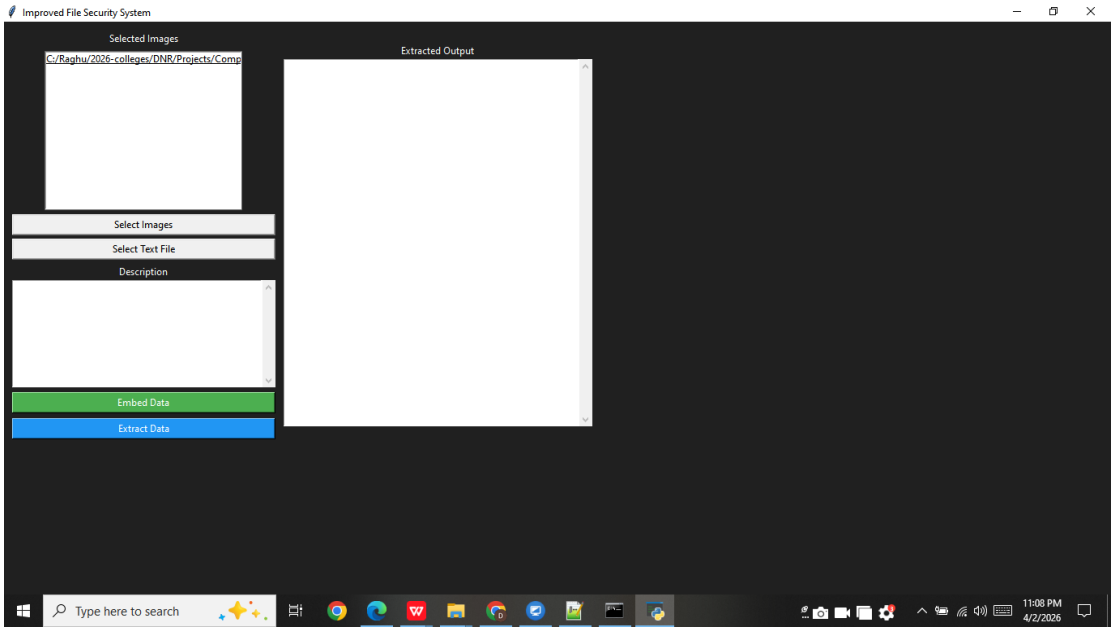
During embedding, data flows from source file through encryption, bit conversion, and pixel modification to output images. During extraction, data flows from carrier images through bit extraction, byte conversion, and decryption to recovered file. The encryption key persists locally, accessed during both embedding and extraction operations.

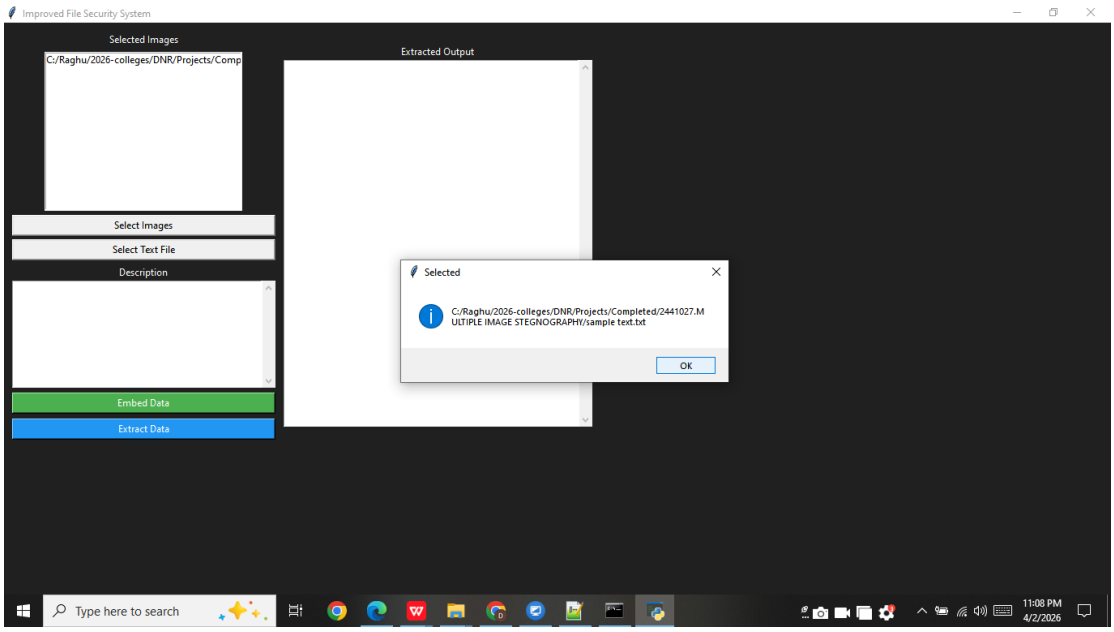
Directory Structure

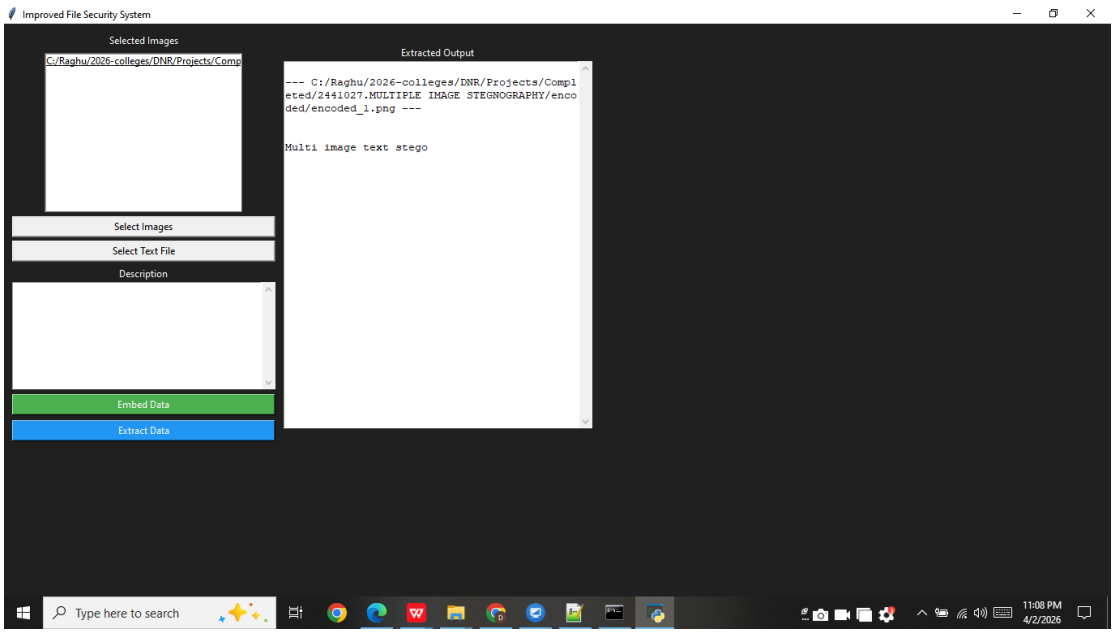
The system creates an output directory for storing modified carrier images, keeping stego-images separate from originals. The encryption key file resides in the working directory, generated automatically if absent.

SYSTEM DESIGN IMAGES









Conclusion

This paper presented a Multi-Image Steganography Security System combining Fernet authenticated encryption with distributed LSB embedding across multiple carrier images. The system addresses capacity limitations of single-image approaches, provides cryptographic protection through established primitives, and offers accessible operation through a graphical interface.

The implementation demonstrates practical feasibility of hybrid cryptographic-steganographic systems for secure covert communication. By encrypting payloads before embedding, the system ensures that extraction without the correct key yields only meaningless ciphertext. By distributing across multiple carriers, the system scales capacity while fragmenting hidden data to complicate analysis.

Limitations include the fixed extraction length currently hardcoded in the implementation, which should instead embed and extract length metadata dynamically. The system also lacks capacity verification before embedding, potentially producing incomplete embeddings for oversized payloads. Future work should address these issues and explore content-adaptive embedding that selects modification locations based on local image complexity to improve resistance against trained steganalysis classifiers.

The system provides educational value for understanding steganographic principles and practical utility for scenarios requiring covert file transmission. The open architecture enables extension toward additional carrier formats, alternative embedding algorithms, and enhanced key management schemes including asymmetric cryptography for multi-party communication.

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