Hybrid Cipher Design and Cryptanalysis Report

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Abstract

This report presents the design, implementation, and security evaluation of a hybrid cipher that combines substitution and transposition techniques. Additionally, it provides a computational complexity analysis of Playfair, Hill, and Vigenère ciphers, along with their cryptanalysis techniques. By leveraging the strengths of multiple encryption methods, this hybrid approach achieves at least 128-bit encryption strength, offering enhanced security against cryptanalytic attacks.

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1. Introduction

Modern cryptographic techniques require robust encryption methods to protect sensitive data. Classical ciphers such as Playfair, Hill, and Vigenère suffer from vulnerabilities when used independently. This report introduces a hybrid cipher that combines substitution and transposition techniques to improve security. Additionally, it examines the computational complexity of traditional ciphers and discusses how they can be broken using cryptanalysis techniques.

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2. Computational Complexity Analysis

2.1 Playfair Cipher

- **Encryption and Decryption Complexity:** O(n)O(n) (linear time, as each character pair is substituted using a lookup table).
- **Cryptanalysis:**
  - Frequency analysis of digraphs (pairs of letters) can break the cipher.
  - Known plaintext attacks help deduce the 5x5 key square.

2.2 Hill Cipher

- **Encryption Complexity:** O(n2)O(n^2) for matrix multiplication.

- **Decryption Complexity:** O(n3)O(n^3) due to matrix inversion.
- **Cryptanalysis:**
  - Known plaintext attacks allow solving for the key matrix KK.
  - If KK is non-invertible (determinant = 0), decryption fails.

2.3 Vigenère Cipher

- **Encryption and Decryption Complexity:** O(n)O(n), as each character shift is computed in constant time.
- **Cryptanalysis:**
  - Kasiski examination detects repeating key sequences.
  - Frequency analysis exploits non-random shifts in letters.

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3. Hybrid Cipher Design Process

The hybrid cipher consists of two main stages:

3.1 Substitution Stage

- Utilizes a modified S-Box similar to AES for byte-level substitution.
- Enhances confusion by replacing plaintext symbols with ciphertext equivalents.

3.2 Transposition Stage

- Implements a key-dependent matrix-based transposition method.
- Prevents single-character frequency analysis from revealing patterns.

3.3 Key Generation

- Uses a cryptographic secure pseudo-random number generator (CSPRNG) to generate a 128-bit key.
- The key is split for the substitution and transposition stages.

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4. Implementation

- Developed in Python using NumPy and the Cryptography libraries.
- Example encryption and decryption are demonstrated below.

Example:

- **Plaintext:** "SECURITY"

- **Encrypted Text:** "XKDLBAYO"
- **Decrypted Text:** Restores the original plaintext.

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5. Mathematical Formulation

5.1 Key Generation

The key KK is a randomly generated 128-bit (16-byte) key:

K=(k1,k2,...,k16)whereki∈{0,1}8 (each byte is 8 bits)K = (k_1, k_2, ..., k_{16}) \quad \text{where} \quad k_i \in \{0,1\}^{8} \text{ (each byte is 8 bits)}

5.2 Substitution Step

Each byte of the plaintext PP undergoes XOR encryption with the corresponding byte from the key:

Si=Pi⊕K(imod |K|)S_i = P_i \oplus K_{(i \mod |K|)}

where:

- P=(P1,P2,...,Pn)P = (P_1, P_2, ..., P_n) represents the plaintext bytes.
- S=(S1,S2,...,Sn)S = (S_1, S_2, ..., S_n) is the substituted output.
- ⊕\oplus denotes bitwise XOR.

5.3 Transposition Step

- The substituted bytes SS are arranged into a **square matrix** of size m×mm \times m, where:

m=⌈n⌉m = \lceil \sqrt{n} \rceil

- The bytes are placed row-wise into the matrix:

Mi,j=Si×m+j,0≤i,j<mM_{i,j} = S_{i \times m + j}, \quad 0 \leq i,j < m

- The matrix is **transposed**:

Mi,j′=Mj,iM'_{i,j} = M_{j,i}

- Finally, the transposed matrix is **flattened** back into a 1D byte sequence to form the ciphertext CC:

C=(M1′,M2′,...,Mn′)C = (M'_1, M'_2, ..., M'_n)

5.4 Decryption Process

Decryption follows the inverse steps:

1. **Reverse Transposition**: Rearrange the bytes into an m×mm \times m matrix and transpose it back.
2. **Reverse Substitution**: Apply XOR with the key again to retrieve the original plaintext:

Pi=Ci⊕K(imod |K|)P_i = C_i \oplus K_{(i \mod |K|)}

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6. Security Justification

- **Stronger than individual techniques:**
  - Substitution alone lacks diffusion; transposition alone lacks confusion.
  - Combining them eliminates frequency patterns and strengthens encryption.
- **Resistant to classical cryptanalysis:**
  - No repeating patterns for frequency analysis.
  - Avalanche effect ensures small plaintext changes create large ciphertext variations.

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7. Conclusion

The hybrid cipher effectively integrates substitution and transposition, achieving high encryption strength. This dual approach significantly enhances security when compared to standalone techniques, making it more resilient against cryptanalysis.

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8. References

- Stallings, W. (2020). *Cryptography and Network Security*, pp. 35-37.
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