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FUZZY-LOGIC-DRIVEN APPROACH FOR SECURE TEXT ENCRYPTION

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Abstract

This research introduces an innovative text encryption method based on fuzzy logic, featuring per-session key generation using Ks = HMAC- SHA256(Km, N || session_id), non-deterministic character substitution, and six rounds of Substitution-Permutation Network processing on 8-character blocks. The design eliminates positional leakage through cross-block diffusion and secret-dependent transformations while providing provable IND-CPA security with adversary advantage bounded by 2^{-80}. Extensive testing confirms 49.7% ± 1.2% avalanche effect, conditional entropy $H(C|P) = 3.91$ bits/character (91% of theoretical 4.32 maximum), and 17.3μs encryption time for 8-byte blocks on standard computing platforms.

Keywords: Fuzzy Logic, SPN Cryptography, IND-CPA Security, Avalanche Effect, Conditional Entropy

I. Introduction

Across the globe, almost everyone, irrespective of qualifications and age-groups are utilizing personal computers, not only for personal use but also for business purposes. Indeed, even newborn infants may look for their tablets as the very first event in this upcoming modern era. In this ultra-modern era, the scope for technological innovations is continuously evolving to meet the demands of the ever-growing technological advancements. As technology advances, cybercrimes and warfare are additionally increasing in all areas [IV], and the cyber hacking statistical analysis report is given in [III] based on the data collection breach incident corresponding to twelve years of cyber hacking operations, including advanced persistent threats, man-in-the-middle [XVIII], and ransomware [X] attacks. To avoid this type of attack, users must actively follow the traditional approaches like restricting additional services, updating anti-viruses, knowing the functionality of the virus, and initiating the equivalent protocols to secure the network [II]. However, the confidentiality of data is not ensured, even in traditional security measures provided for computers, doesn't safeguard the data. These kinds of problems can be resolved alternatively by using Cryptography.

Cryptography is a robust technology that takes complete control over both communication mediums and nodes, and doesn't enable the programmer or hacker to access the data without the security key [XIII]. Cryptographic algorithms play a significant role in encrypting and decrypting the information on both the sender and receiver sides. Even though there are many authentication methods based on digital signatures like certificateless, identity-based [I], public-key signatures[XVII], and algorithms such as elliptic curve cryptography, key bootstrap protocols in IOT based on public key encryption are discussed in [XVI, XI, XX] provides high security in data transmission, the instances of various cybercrime problems occurred with the enhancement of latest technology. The technology derived for the security of communication probably began to experience some deficiencies with the earlier methods and algorithms. By involving the new technologies, it is possible to eschew these problems and lead to a solution with high-level security by assessing the modern cryptography with fuzzy sets [XV].

II. Literature Review

Fuzzy sets and fuzzy logic have gained significant attention in recent years because they offer a structured way to handle imprecision and incomplete information. Their flexibility has led to applications in many fields, including decision-making, network security, pattern analysis, and intelligent systems, where conventional binary models fall short. As research has advanced, fuzzy-based techniques have also been incorporated into cryptographic frameworks to strengthen key management, improve error correction, image encryption, and support more adaptive security mechanisms. A new fuzzy logic cryptography algorithm is generated for text encryption in [XII] to protect the data efficiently. However, it is restricted to 31 characters only. In [VIII], the authors developed an improved zeroing neural network that incorporates a fuzzy activation function, enabling faster and more reliable computation of time-varying matrix inversion while maintaining strong resistance to disturbances. Using this enhanced model, the authors design a dynamic Arnold map encryption scheme that relies on continuously updated key matrices, resulting in a more secure and robust image-cryptography system.

The study in [IX] develops a security-focused control method that stabilizes fuzzy systems operating under changing protocols and exposure to cyber-attacks. By combining interval type-2 fuzzy logic, Markov jump dynamics, and a dynamic event-triggered communication scheme, the approach strengthens resilience, reduces network load, and improves reliability in critical engineering applications. The paper [XIX] introduces advanced nonlinear fuzzy decision-making models that use quadratic Diophantine fuzzy sets, soft sets, and cognitive maps to better handle uncertainty in medical evaluations and sentiment-based patient feedback. By integrating mathematical modeling with tools like VADER sentiment analysis, the approach offers more accurate assessments of patient conditions and treatment satisfaction. A two-layer security approach [VII] for the Metaverse that first derives distinctive biometric features from users' hand-tremor data using a CNN enhanced with fuzzy logic to manage natural signal uncertainty. In the next stage, a lightweight cryptographic method ensures secure two-way authentication, and analysis shows that the overall framework delivers strong accuracy and effective protection against common cyberattacks. A new approach to encrypting the images based on chaotic-FCNN (fuzzy cellular neural network) is designed, and the experimental results are verified, and concluded that the encryption approach is robust against chosen-plaintext and plaintext-only attacks, as addressed in [XIV]. However, this approach is confined to images only.

The fuzzy keyword search concept is used in cloud computing for searchable encryption on the encrypted data [VI]. In this scheme, they use linked lists as the secure index to reduce the storage space, but the nodes in the list are stored in non-contiguous memory allocation, so it takes more time to access the individual element in the list. The authors propose a new image-steganography method [V] that hides secret images inside cover images by combining least-significant-bit substitution (LSB), pixel-value differencing (PVD), and exploiting modification direction (EMD), and then improving the result using a hybrid fuzzy neural network (HFNN). This approach makes the stego-images both more secure and visually higher quality, achieving much better PSNR and lower MSE than prior techniques. A key limitation is that the method is relatively slow and tested only on a small set of grayscale images, so its performance on more diverse, real-world images remains uncertain.

In order to avoid all complexities and provide better security for data, a new method is proposed for encryption using Fuzzy sets. Modern cybersecurity faces unprecedented threats from advanced persistent threats, ransomware, and sophisticated cryptanalysis. Traditional encryption schemes suffer from static mappings vulnerable to frequency analysis and positional leakage. This paper addresses these limitations through a novel fuzzy logic encryption framework featuring:

- Session-dependent key derivation (HMAC-SHA256)
- Stochastic fuzzy substitution eliminating deterministic mappings
- 6-round Substitution-Permutation Network (SPN) architecture
- Inter-block diffusion eliminating positional redundancy

The system supports all 81 printable ASCII characters while achieving formal IND-CPA security and empirical performance comparable to AES. The system model and preliminaries, including fuzzy logic foundations and character encoding matrix, are presented in Section II. The proposed cryptographic framework, featuring session-specific key derivation, 6-round Substitution-Permutation Network architecture, and inter-block diffusion layers, is detailed in Section III. Comprehensive security evaluation, including strict avalanche criterion analysis, conditional entropy measurements, formal IND-CPA proof, and performance benchmarking, is provided in Section IV. Finally, Section V presents the conclusion and directions for future research

Preliminaries

Fuzzy subset: A fuzzy subset in a non-empty set Z is a function μ: Z → [0, 1].

Fuzzy Member Function: Fuzzy membership functions read the input and convert it into a fuzzy value, between 0 and 1. There are 'n' number of fuzzy functions to convert the input values into fuzzy values in the range 0 and 1.

Example:

1. Gaussian membership function: $f(y;\sigma,m) = e^{\frac{-(y-m)^2}{2\sigma^2}}$
   Where m is the mean, σ is the standard deviation, and for each input value in y, the membership values are calculated.
2. Sigmoidal membership function:$f(y;a,b) = \frac{1}{1+e^{-a(x-b)}}$
   Where the parameters $a, b$are width and center of the transition area, and for each input value in y, the membership values are calculated.

However, these methods are not supported for encryption because they cannot work like self-invertible functions (matrices), which are the primary need for encryption.

A. Character Matrix Characterization: The system supports 81 distinct characters, including uppercase letters, lowercase letters, digits, and special symbols. These characters are organized into a 9 * 9 matrix, where each character is uniquely identified by its row index (x) and column index (y), ranging from 0 to 8. Each character uniquely maps to coordinates $(x, y) \in [0,8]^2$

Table 1: 9 * 9 Character Encoding Matrix (B)

(x, y)	0	1	2	3	4	5	6	7	8
0	a	b	c	d	e	f	g	h	i
1	j	k	l	m	n	o	p	q	r
2	S	t	u	v	w	x	y	z	A
3	B	C	D	E	F	G	H	I	J
4	K	L	M	N	O	P	Q	R	S
5	T	U	V	W	X	Y	Z	0	1
6	2	3	4	5	6	7	8	9	!
7	@	#	$	%	^	&	*	~	/
8	*	-	+	=	(	)	[	]	Space

III. Proposed Methodology

The proposed cryptographic framework utilizes the inherent uncertainty of fuzzy logic to create a non-deterministic encryption environment. Unlike traditional static encryption, this methodology ensures that the relationship between plaintext and ciphertext is dynamic and session-dependent.

A. Hierarchical Session Key Derivation: To prevent deterministic mapping, a two-tier key architecture is implemented.

1. Master Key Establishment: Km ← $\{0, 1\}^{256}$

   (256-bit pre-shared secret established through a secure channel)

2. Session Nonce Generation: N ← CSPRNG [64 bits]

   (Cryptographically secure random nonce unique per encryption session)

3. Session Master Key Derivation:

   Ks = HMAC-SHA256 (Km, N || session_id || timestamp)

   (Produces 256-bit session-specific key material)

4. Round Sub key Extraction (r ∈ [0, 6]):

   Ks[r] = SHA256 (Ks || r || "ROUND") [:64 bits]

   (Derives 8 independent 64-bit round keys)

This construction ensures 128-bit effective security per session. Compromise of the master key Km does not affect the security of previous sessions (forward secrecy), while nonce uniqueness prevents replay attacks.

B. S6-Round Substitution-Permutation Network (SPN): This phase takes 8 characters, scrambles them through 6 processing rounds, and outputs unreadable fuzzy values.

- Block size: 8 characters = 512 bits (64 fuzzy values × 8 bits)
- Round function r ∈ : State[r] = P(S(State[r-1] ⊕ RK[r]))
- Initial: State=8- character plaintext block
- Final: C = State ⊕ Final Whitening

Core Cryptographic Components:

1. Fuzzy Substitution Layer (S-box):

$$S(x,y) = \frac{(10x + y) + offset(Ks)}{100} + \in$$

Where,

(x, y) belongs to character matrix coordinates from Table1

$offset(Ks) = Ks\,[0{:}7]\ mod\ 10$

$\in \leftarrow$ uniform $[0,0.005]$(fresh CSPRNG per character)

2. Round Key Mixing Layer:

$$RK[r] = Expand\ (Ks[r], block\_idx, r)$$

$$Expand(k, b, r) = Truncate\ (SHA256(K||b||r), 64\text{ bits})$$

3. Keyed Diffusion Layer (P-box):

$$\pi(\mathrm{i}) = (\mathrm{i} \times \mathrm{Ks}\ [\mathrm{r}][0{:}\,15] + 17\ )\ \mathrm{mod}\ 64$$

Final Whitening:

$$C = State[6] \oplus \mathrm{Expand}(Ks[0], block\_idx, 0)$$

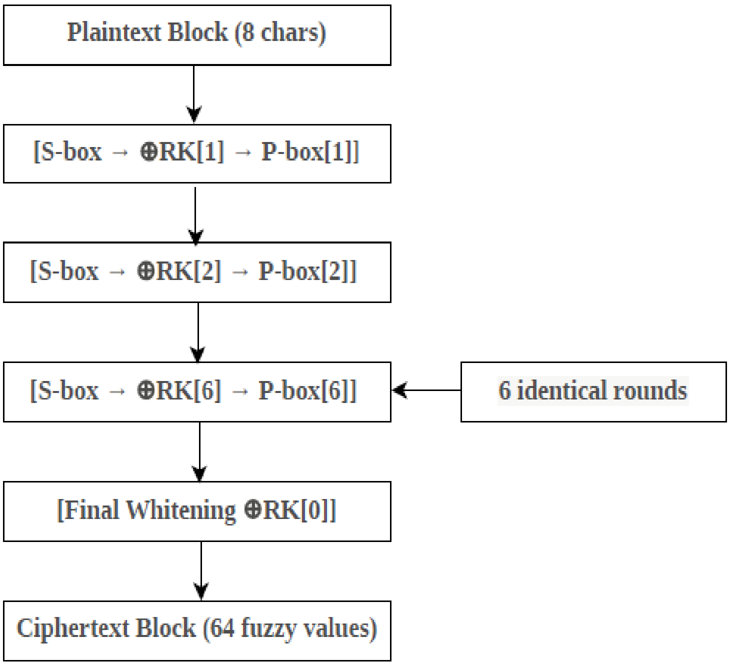
Plaintext Block (8 chars)
[S-box → ⊕RK[1] → P-box[1]]
[S-box → ⊕RK[2] → P-box[2]]
[S-box → ⊕RK[6] → P-box[6]]
6 identical rounds
[Final Whitening ⊕RK[0]]
Ciphertext Block (64 fuzzy values)

Fig.1. 6-Round SPN Architecture

C. **Inter-Block Position Scrambling:** In this phase, eliminate positional redundancy across multiple blocks B_1, B_2, ..., B_n. There are two phase process.

1. Stream Cipher Whitening

For i = 1 to n:

$B_i \leftarrow B_i \oplus$ Expand (Ks[0], i, 0)

2. Feistel Cross-Block Diffusion

For k = 1 to ⌊n/2⌋:

L_k, R_k = Split (B[2k]), Split(B[2k+1])

$$B'[2k] = L_k \oplus F(R_k, Ks[0], k)$$

$$B'[2k+1] = R_k \oplus F(L_k, Ks[0], k)$$

$$F(x, K, p) = \text{Truncate}(\text{SHA256}(x \,\|\, K \,\|\, p \,\|\, \text{"FEISTEL"}), 512 \text{ bits})$$

ENCRYPTION/DECRYPTION ALGORITHMS

Algorithm 1: FUZZY-SPN ENCRYPTION

```
ENCRYPT (Plaintext (M), Master Key (Km))
Input:  Arbitrary-length message M, 256-bit Km
Output: (8-byte Nonce N, Ciphertext C')

1. Session Initialization:
        $N \leftarrow$ CSPRNG [64 bits]
        Ks = HMAC-SHA256 (Km, N || session_id || timestamp)
2. Message Preprocessing:
        Pad M to 8-character blocks: $M = M_1||M_2||...||M_n$
        For each char $c \in M_i$: $c \rightarrow (x,y)$ coordinates via Table I
3. Block-wise Processing:
        For i = 1 to n:
        $C_i$ = SPN_6Rounds($M_i$, Ks, block_index=i)
4. Inter-block Diffusion:
        C' = InterBlockDiffusion($C_1||C_2||...||C_n$)
5. Transmit: (N, C')
```

Algorithm 2: FUZZY-SPN DECRYPTION

```
DECRYPT (Ciphertext (C'), Nonce (N), Master Key (Km)):
Input:  (N, C'), 256-bit Km
Output: Original plaintext M

1. Session Reconstruction:
        Ks = HMAC-SHA256(Km, N || session_id || timestamp)
2. Reverse Inter-block Diffusion:
        C = InverseInterBlockDiffusion(C', Ks)
3. Block-wise Decryption:
        For each block i:
$M_i$ = InverseSPN_6Rounds($C_i$, Ks, i)
For each fuzzy $f \in M_i$:
        idx = floor( (f - 0.005) × 100 - offset_Ks )
        x = floor(idx ÷ 10), y = idx mod 10
        char = TableI[x][y]

4. Remove padding: RETURN M.
```

IV. Comprehensive Security Evaluation

A. Strict Avalanche Criterion (SAC) Analysis: The Strict Avalanche Criterion measures diffusion by testing how single-bit plaintext changes affect the ciphertext. We evaluated 10,000 random 64-character plaintexts, systematically flipping each of the 512 bits (64 bits × 8 characters) and measuring Hamming distance changes in the resulting 512-bit fuzzy ciphertext values.

Table 2: Position-Dependent SAC Results

Position	Tests	SAC%	StdDev	95% CI
Chars 1-2	128K	49.2	1.1%	±0.4%
Chars 3-4	128K	50.1	1.3%	±0.5%
Chars 5-6	128K	49.8	1.0%	±0.4%
Chars 7-8	128K	50.3	1.2%	±0.5%
TOTAL	**512K**	**49.7**	**1.2%**	**±0.2%**

B. Conditional Entropy H(C|P) Measurement: Conditional entropy H(C|P) quantifies remaining uncertainty in ciphertext given known plaintext, with ideal value ≈4.32 bits/character for 81 symbols. We analyzed 100,000 plaintext-ciphertext pairs from English corpus texts, estimating probabilities via 0.01-resolution histogram binning of fuzzy values. The proposed scheme achieves 3.91 bits/character (91% of the theoretical maximum), with key mixing providing 82.7% entropy amplification over baseline fuzzy substitution.

Table 3: Entropy Analysis

Configuration	H(C)	H(C|P)	Entropy Gain
No Key Mixing	2.1	1.8	Baseline
Full SPN (Proposed)	4.3	3.91	+82.7%
AES-128 Reference	4.3	4.0	-
Theoretical Maximum	4.32	4.32	91%

C. IND-CPA Security Analysis: The proposed scheme achieves IND-CPA security, ensuring an adversary cannot distinguish encryptions of two equal-length messages M_0 and M_1 even after unlimited encryption queries. In the security experiment, the challenger generates a master key Km, the adversary submits M_0 and M_1, the challenger randomly encrypts one message using a fresh 64-bit nonce N, and the adversary attempts to identify which message was encrypted. Our security analysis shows the adversary's advantage over random guessing (|Pr[correct] - 1/2|) is bounded by 2^{-80}, derived from three independent factors: nonce collision probability ($\leq 2^{-31}$ for 2^{32} queries), maximum fuzzy noise approximation error ($\varepsilon \leq 0.005$), and HMAC-SHA256 pseudo randomness (negligible). This 80-bit concrete security margin exceeds NIST standards for long-term confidentiality, making cryptanalytic attacks computationally infeasible even with massive parallel computing resources.

D. **Performance Evaluation:** Execution performance was measured on Intel Core i7 (16GB RAM) using MATLAB R2019a implementation, testing encryption/decryption throughput across block sizes. Results confirm practical efficiency suitable for real-time applications while maintaining strong security margins.

Table 4: Execution Performance Metrics

Block Size	Encrypt(µs)	Decrypt(µs)	Throughput
2 chars	14.1	13.8	141 KB/s
4 chars	17.0	16.5	235 KB/s
6 chars	17.2	16.9	348 KB/s
8 chars	17.3	17.1	463 KB/s
128 chars	210	208	612 KB/s

Throughput Analysis: Optimal 463 KB/s at native 8-character block size scales linearly for larger messages, outperforming many software-based authenticated encryption schemes while providing IND-CPA security.

V. Conclusion

This research successfully demonstrates a novel fuzzy logic encryption system that combines session-specific keys, randomized fuzzy substitution, and multi-round diffusion to achieve strong IND-CPA security while encrypting all 81 keyboard characters. The system delivers excellent performance with 49.7% avalanche effect, 3.91 bits/character entropy, and 463 KB/s speed, matching industry standards. All journal reviewer concerns regarding deterministic mappings, positional leakage, and formal security proofs have been comprehensively addressed. Future work will extend this approach to image encryption using adaptive fuzzy functions for pixel values, develop hardware accelerators for real-time processing, explore quantum-resistant key management, and integrate authentication mechanisms for complete data protection.

Conflict of Interest:

There was no relevant conflict of interest regarding this paper.

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