Image encryption using dynamic DNA encoding and pixel scrambling using composite chaotic maps

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Abstract: In this digital world, encryption plays an important role in various domains. Securing the information is the main goal when transfer of information takes place. Image encryption is a very important part of this as it applies to various domains like medical, multimedia, defence etc. A new method for image encryption is proposed here taking into account the “confusion-diffusion” structure. While working with secure data, requirements like fast computation, compression and processing are important issues. Deoxyribonucleic Acid (DNA) encoding has the capability to cope up with this requirement. In this paper a new algorithm is proposed based on composite chaos map for pixel scrambling and hence image encryption. First the algorithm takes the image and XORs with a composite chaotic map which further goes into dynamic DNA encoding followed by pixel scrambling which results in the image being very random thus it becomes less prone to attacks. The method discussed performs efficiently as shown in the experimental results.

Keywords: Composite Chaotic Map, Dynamic DNA encoding, Pixel Scrambling, Image Encryption.

1. INTRODUCTION

As technology is getting advanced day-by-day, an image is vastly used in all the domains. Hence, a powerful and an efficient cryptographic method is required for at ease image transmission and storage. The existing techniques like Data Encryption Standard (DES) and Advanced Encryption Standard (AES) for encryption does not fulfil the requirements of image encryption as they have low performance measures in terms of efficiency and security [1]. To achieve a secure cryptosystem, an image encryption algorithm consists of many phases such as permutation, substitution, diffusion, confusion etc.
Cryptography based on DNA is predicated on the various DNA characteristics in accordance with methods to increase safety and efficiency. The advantages of these methods are the self-assembling standards of the Molecules, capability of computing parallelly and huge storage capabilities [2]. After years of research and study on DNA, researchers have concluded that the DNA sequence has a quaternary combination, which can be compared to the semiconductors on & off system[3]. An equivalent phenomenon which can be seen in a deterministic system is chaos and is a very interesting and important topic in the field of non-linear science. A chaotic system has the ability of generating sequence repetitively, rapidly which makes it perfect for encryption of images. It is because chaos has a natural reference to cryptography so more and more scientists and researchers are focusing on the chaotic image encryption.

Using DNA encoding technique, the data can be stored and calculated using randomness of the nucleotides [4] & [5]. A method was introduced called OTP which was based on DNA. The cryptography had two such kind of schemes [6]. Proposed a cryptography method that made use of deoxyribonucleic acid sequence [7]. Took the help of these sequences to resolve the key distribution issue [8]. Introduced a scheme that used a method of contrast mapping to insert values into any random part of a deoxyribonucleic acid sequence. Also, this didn’t affect the function of the acid [9].

The encryption methods based on DNA, results in high computing power and also in the capabilities of storing the data. In the recent years, many algorithms were introduced which combined the traditional ciphers and the DNA to result in more efficient algorithms. In 2014, an algorithm was proposed which was based on chaos map and encoding [10]. In the year 2015, an algorithm that was based on DNA and logistics mapping (2D) [11]. An encryption algorithm which worked on the combination of DNA and chaos map [12].

This paper has a target of increasing the efficiency and security of the encryption algorithm over the older cryptosystem methods such as Elliptic Curve Cryptography (ECC), Rivest–Shamir–Adleman (RSA) etc. The multi-fold security makes this method more efficient. The rest of this paper is presented in the following order – Section 2 has the Related Works presented in it to discuss about the various maps that are used in the paper. The methodology, algorithm and the steps used are explained in section 3 while the next section- Section 4 illustrates the results of encryption of five test images. Section 5 concludes the paper.

2. RELATED WORKS

2.1. Dynamic DNA Encoding

Every DNA molecule has 4 DNA nucleotides which are cytosine (C), adenine (A), thymine (T), and guanine (G). The stability of a DNA molecule is based on the Hydrogen (H)-bonds formation between the nucleotides of two single-stranded DNA molecules. G and C nucleotides are paired by 3 H-bonds, whereas the A and T nucleotides are paired by 2 H-bonds as per the base pairing principle by Watson-Crick. Naturally they combine quaternary and so, the permutations and combinations of these base nucleotides store the information and also helps in further calculations. The pixel confusion in DNA coding is achieved by the definition of the rules shown in table 1.

The paper proposes a dynamic algorithm by using a chaotic map to dynamically index the rule selection in the confusion process for every pixel, making the confusion process even harder for attacks. For example, if the value in sixty-sixth row and sixty-fifth column of the original image is
198, which in binary is [11000110], the encoded DNA pixel sequence is [ATGC] considering the developed dynamic encoding technology to select the encoding rule 8 for that pixel.

| Rule | I | II | III | IV | V | VI | VII | VIII |
|------|---|----|-----|----|---|----|-----|------|
| 00   | A | A  | C   | G  | C | G  | T   | T    |
| 01   | C | G  | A   | A  | T | T  | C   | G    |
| 10   | G | C  | T   | T  | A | A  | G   | C    |
| 11   | T | T  | G   | C  | G | C  | A   | A    |

Table 2 containing the base transforming rule is used to induce disturbance in the pixel value.

| XOR | A | C | G | T |
|-----|---|---|---|---|
| A   | A | C | G | T |
| C   | C | A | T | G |
| G   | G | T | A | C |
| T   | T | G | C | A |

2.2. Composite map pixel scrambling

Image scrambling is a good method for providing security to image data by making it difficult to decrypt it for unauthorized users. Our algorithm divides the image matrix into 16 sub-blocks as shown in the figure 1 and each of these blocks is rotated to a measure of 90° in the clockwise direction. These rotated blocks undergo pixel scrambling separately using the key generated from 8 different chaotic maps. Every key is indexed to two of these 16 blocks using a separate chaotic sequence of length 16 containing unique indexes. This algorithm not only provides randomness to the chaotic map allotment to these blocks but also provides chaos at the scrambling sequences by the individuality provided by the eight maps used.

![Figure 1. Scrambling Procedure](image)
2.3. XOR function

The bitwise XOR operation is used here as a part of a more complex encryption algorithm. XOR is used as a step after every major encryption process in every iteration of the procedure to increase the complexity of encryption. Two different chaotic sequences are generated. Each of it is circular-shifted with itself to generate a key. The two such keys generated are XOR-ed with the image matrix to result in a resultant image matrix.

2.4. Chaotic mappings

Chaotic maps use the chaos theory on deterministic systems whose behaviour over time can be predicted by theory. The main idea that is used here in these maps is that a minute difference at the beginning of the mapping can result in a huge change in the final result as time increases. In these maps, the uncertainty increases exponentially with time. Several chaotic maps are prepared till date [13] and few of them that are used in proposed algorithm are explained below.

2.4.1 Quadratic map. This map is a very primitive chaotic map, and its classical version is,

\[ P_{n+1} = a - (P_n)^2 \]  

where \( a \) is the parameter for chaos and \( n \) being the total iterations. The map’s chaos is due to its nonlinearity. When \( a \) is in the range of \([1.5, 2]\), the system turns chaotic, which can be seen in figure 2.

![Figure 2. Chaos at a=1.9.](image)

2.4.2 Logistic map. A straightforward easy map is the logistic map with the polynomial equation:

\[ P_{n+1} = b \cdot P_n \cdot (1 - P_n) \]  

where ‘\( b \)’ is the bifurcation factor and \( P_n \) implying \( n^{th} \) generation population and. As the growth rate ‘\( b \)’ is altered, this map shows a range of behaviour the change in initial conditions makes the map very sensitive. When \( P_n \) belongs to \([0, 1]\), Parameter ‘\( b \)’ belongs to \([3.569946, 4]\) and also \( b \in N \), the generated sequence illustrates chaos as shown in the bifurcation diagram, figure 3.

![Figure 3. Logistic map’s bifurcation diagram](image)
2.4.3 Singer map. The Singer map [14] represents the iterated function or otherwise the chaotic map as defined by:

\[
P_{n+1} = r^* (7.86 \times P_n - 23.31 \times P_n^2 + 28.75 \times P_n^3 - 13.3 \times P_n^4)
\]  
(3)

where \( r \), the chaotic parameter lies in \([0.9, 1.08]\). The chaotic sequence is generated in the interval \( P_n \in [0, 1] \).

2.4.4 Sine map. This chaotic sequence is generated from an iterative function which contains sine itself and is defined as:

\[
P_{n+1} = x \times \sin(\pi \times P_n)
\]  
(4)

where \( 0 \leq x \leq 1 \). The sequence obtained in this map is in the interval \( P_n \in [0, 1] \).

2.4.5 Piecewise map (pwcm). The pwcm is an iterative function consisting of four linear parts that are calculated by the function:

\[
A_{n+1} = \begin{cases} 
\frac{A_n}{p}, & 0 \leq A_n < p \\
\frac{A_n - p}{0.5 - p}, & p \leq A_n < 0.5 \\
\frac{1 - A_n - p}{0.5 - p}, & 0.5 \leq A_n < 1 - p \\
\frac{1 - A_n}{p}, & 1 - p \leq A_n < 1 
\end{cases}
\]  
(5)

where \( p \in [0, 0.5] \). The resultant chaotic sequence \( A_n \) is in the interval \([0, 1]\).

2.4.6 Lorenz map. Lorenz map is determined by the following iterative method:

\[
a' = x(b-a)
b' = y*a - b - a
\]  
(6)

where \( x \) denotes Prandtl number, \( y \) denotes Rayleigh number and \( z \) being an aspect-ratio. The apostrophe notation is used to denote the derivatives w.r.t. time. Though not all solutions of the Lorenz system are chaotic, when \( y = 28 \), \( a = 10 \) and \( z = 8/3 \), the solutions are chaotic in nature.

2.4.7 Ikeda map. A dynamic system over discrete-time given by the complex map:

\[
a_{n+1} = 1 + x(a_n \cos t_n - b_n \sin t_n)
b_{n+1} = x(a_n \sin t_n + b_n \cos t_n)
\]  
(7)

where \( x \) is a chaos parameter and \( t_n = 0.4 - 6/(1 + a_n^2 + b_n^2) \). The map has a chaotic attractor for values of \( x > = 0.6 \).

2.4.8 Henon map. Being one of the most used variant of dynamic systems that shows chaotic nature, this map is a dynamic system of discrete-time. A new point is mapped to a point \((x_n, y_n)\) in the plane by this map:

\[
P_{n+1} = 1 - x \times P_n^2 + Q_n
\]

\[
Q_{n+1} = y \times P_n
\]  
(8)

where the 2 parameters of values, \( x = 1.4 \) and \( y = 0.3 \) makes it a classical version of the Henon map which always stays chaotic because for few other values of these two parameters, \( x \) and \( y \) the
map might be either chaotic, intermittent, or can even converge to a periodic orbit making it non-chaotic.

2.4.9 Coupled Logistic-Sine (CLS) map.

\[ P_n = \text{mod}(rP_n - 1 \ast (1 - P_n - 1) + (4 - r) \ast \sin(\pi P_n - 1)/4, 1) \]  

(9)

The system is chaotic in [0, 4] interval.

2.4.10 Coupled Logistic-Tent (CLT) map.

The representation of the map is as follows-

\[
A_n = \begin{cases} 
\text{mod}(\beta A_{n-1} \ast (1 - A_{n-1}) + \frac{(4-\beta)\ast A_{n-1}}{2}, 1); & \text{for } A_n < 1/2 \\
\text{mod}(\beta A_{n-1} \ast (1 - A_{n-1}) + \frac{(4-\beta)\ast (1-A_{n-1})}{2}, 1); & \text{for } A_n \geq 1/2 
\end{cases}
\]

(10)

where \( \beta \) is the control parameter and makes the system chaotic in the interval [0,4].

2.4.11 Circle map. This 1-D map, maps itself to a circle. The equation is

\[
\beta_{n+1} = \beta_n + \theta - (K/2\pi) \ast \sin(2\pi \beta_n) 
\]

(11)

where \( \beta_{n+1} \) is calculated to mod 1. This map has 2 parameters, namely, \( \theta \) which is the term for externally applied frequency, and \( K \) being a term for strength of nonlinearity.

Table 3 presents the chaotic maps used in this algorithm and their chaotic ranges with the remarks of at what step is the chaotic map being used.

| S. No. | Chaotic Map | Parameters/Chaos Range | Remarks |
|--------|-------------|------------------------|---------|
| 1.     | Quadratic   | \( a = \{1.5, 2\}, n \) | Used in pixel scrambling |
| 2.     | Logistic    | \( b = \{3.56, 4\}, n \) | Used in DNA encoding, pixel scrambling |
| 3.     | Singer      | \( r = \{0.9, 1.08\}, n \) | Used for chaotic map selection in pixel scrambling |
| 4.     | Sine        | \( x = \{0, 1\}, n \) | Used in DNA encoding, pixel scrambling |
| 5.     | Pwlcm       | \( A_n = \{0, 1\} \) | Used in pixel scrambling |
|        |             | \( p = \{0, 0.5\} \) | |
| 6.     | Lorenz      | \( y = 28, a = 10 \text{ and } z = 8/3 \) | Used in pixel scrambling |
| 7.     | Ikeda       | \( x > = \{0.6\} \) | Used in pixel scrambling |
| 8.     | Henon       | \( x = \{1.4\}; y = \{0.3\} \) | Used in pixel scrambling |
| 9.     | Tent        | \( b = 2 \) | Used in pixel scrambling |
3. PROPOSED METHODOLOGY

3.1. Encryption

The flow chart proposed algorithm is shown in figure 4. This encryption process has several steps that are described below:

Step 1. Grayscale input image \( im \) is taken as a 2-D matrix \( I_1 \) of size \( m \times n \).

Step 2. The XOR function generates two keys \( k_1 \) & \( k_2 \) from two chaotic maps. Key \( k_1 \) is XORed with \( I_1 \) and the resultant is XORed with key \( k_2 \) to obtain image matrix \( I_2 \).

Step 3. A chaotic logistic map is used for the rule selection during the dynamic DNA encoding process. The DNA encoded Matrix is later DNA-XORed (table 2) with a DNA Encoded chaotic SINE map. The DNA-XORed Matrix is then encoded with Codebook rule 3 (table 1) and then converted into an image matrix \( I_3 \).

Step 4. Step 2 is repeated with image matrix \( I_3 \) to produce image matrix \( I_4 \).

Step 5. The image Matrix \( I_4 \) is divided into 16 sub-blocks. A total of 8 chaotic maps are used in the pixel scrambling process to permute the pixel position of the image matrix \( I_4 \). A Singer map is used to randomize the use of these 8 chaotic maps on the 16 sub-blocks. Finally, these 16 sub-blocks are merged into image matrix \( I_5 \).

Step 6. Step 2 is repeated with image matrix \( I_5 \) to produce image matrix \( I_6 \).

Step 7. A second iteration of encoding and scrambling process takes place by performing the steps 3 to 6 on Image matrix \( I_6 \) generating the final transmitted encrypted image.

Figure 4. Encryption Algorithm
3.2. Decryption

The decryption process has several steps that are described below:

Step 1. The initial conditions and control parameters for every chaotic map and the encrypted matrix are obtained. Decryption process works in the opposite order of the encryption.

Step 2. The Reverse XOR works in the opposite way of XOR. The encrypted image is XORed with key k2 & the result is then XORed with key k1.

Step 3. For pixel unscrambling, the 8 maps used for pixel scrambling should be regenerated and singler map with same initial conditions would give the indexes of the 8 chaotic maps to be used for unscrambling. The result from step 2 is be divided into 16 sub blocks and 8 maps are used to unscramble the image matrix.

Step 4. Step 2 is repeated on the result obtained from step 3.

Step 5. Chaotic SINE map is generated to create a chaotic sequence which is used to create the DNA decoded sequence. The same DNA-XOR truth table is used to decrypt the image matrix obtained from step 4 and the dynamic DNA decoding process takes place followed by Reverse XOR.

Step 6. A second iteration of the decoding and unscrambling process happens performing the steps 2 to 5 generating the original image.

4. RESULTS

4.1. Performance Analysis

4.1.1 Histogram Analysis. Input and encrypted image histograms are plotted. Original image’s histogram shows a non-uniform form whereas the histogram of encrypted image shows uniform nature, proving that the working of DNA encoding & pixel scrambling by chaotic maps.

4.1.2 NPCR and UACI. Number of Pixel Change Rate (NPCR) and Unified Average Changed Intensity (UACI) [15] are metrics used to assess the robustness of the encryption process for protection against attacks mainly spatial attacks. Let \( P_1(j,k) \) is pixel value at point \((j,k)\) before encryption and \( P_2(j,k) \) is pixel value at point \((j,k)\) after encryption and \( F \) be the largest pixel to fit.

\[
D(j,k) = \begin{cases} 
0, & \text{if } P_1(j,k) = P_2(j,k) \\
1, & \text{if } P_1(j,k) \neq P_2(j,k) 
\end{cases}
\]

\[
NPCR = \frac{\sum D(j,k)}{N} \times 100\% \tag{12}
\]

\[
UACI = \frac{\sum |P_1(j,k) - P_2(j,k)|}{(F \cdot N)} \times 100\%
\]

4.1.3 Correlation Coefficient. A statistical metric used to evaluate the similarity between variables and gives information about the relationship between two adjacent pixels in diagonal, horizontal and vertical, directions. Lower the value of correlation coefficient between two pixels, better will be the confusion in the image. A negative correlation coefficient between 2 adjacent pixels shows an inverse relationship between them.
4.1.4 Structural Similarity Index (SSIM). A perceptual metric which evaluates the degradation of image quality due to external factors. It includes luminance masking and contrast masking terms. In case of spatial damages to the image SSIM can be a reliable metric for quantifies perceived change in structural information.

4.2. Simulation Results

MATLAB R2019a software was used to develop and test this algorithm. Lena.jpg, Cameraman.tif, peppers.png, canoe.tif and tape.png are the test images used. All the images are demo MATLAB images preloaded in the software built.

As per table 4(b) Entropy for every image tested lies in range >7.99 which is ideal for an encrypted image. The correlation between pixels is very less (ideal) in all the images tested.

NPCR & UACI quantities were also taken into account for testing of strength of the algorithm. NPCR lies in between 99.36-99.56 whereas UACI is 33% ideal for an encrypted image. SSIM was also considered between the original and the encrypted image. For all test images SSIM was less than 1%. Correlation coefficient between the original and encrypted images were taken which was well under 10% in all the cases. The SSIM and correlation coefficient values can be seen in table 4(a).

Plots of Horizontal, Vertical, and Diagonal Correlation are also shown in figure 7. These images show that the correlation of original image pixel intensifies in a particular rangewhileas the encrypted image’s horizontal, vertical, diagonal correlation of pixels remain uniform. Figure 5 shows the original and the encrypted images and their respective histograms. It can be observed that the encrypted image histogram displayed is evenly spread out as per requirements.

These results imply that this algorithm has a high key sensitivity, strong key space which is not crackable by brute force, performance parameters which are ideal as per standards.

| Test Images | SSIM | Correlation Coefficient |
|-------------|------|-------------------------|
| Lena        | 0.0102 | 0.0031 |
| Cameraman   | 0.0069 | -0.0072 |
| Peppers     | 0.0090 | 0.0022 |
| Canoe       | 0.0086 | -0.0029 |
| Tape        | 0.0071 | -0.0020 |
Figure 5. Experimental results: (5.1) Original image; (5.2) Histogram of original image; (5.3) Encrypted image; (5.4) Histogram of encrypted image.

Figure 6. Decrypted Images: (a) Decrypted through Key Set – 1 from table 5; (b) Decrypted through Key Set – 2 from table 5.

Figure 7. Experimental results for; (a) Horizontal Correlation-Original Image; (b) Horizontal Correlation-Encrypted Image; (c) Vertical Correlation-Original Image; (d) Vertical Correlation-Encrypted Image; (e) Diagonal Correlation-Original Image; (f) Diagonal Correlation-Encrypted Image.

Table 5 shows different key sets for the proposed algorithm. Key Set-1 is the original set used at encryption side. Key Set-2 is the changed set at the underlined position. Figure 6 shows that Key-set 1 can decrypt the encrypted image correctly, Key Set-2 with changed value couldn’t decrypt. Key Space for this algorithm is $10^{(\text{No of parameters}) \cdot (\text{No of decimals in each})} = 10^{180}$. 


### Table 4(b). Performance analysis Original and Encrypted Image

| TEST IMAGES | ENTROPY | CORRELATION COEFFICIENTS | NPCR | UACI |
|-------------|---------|---------------------------|------|------|
|             | ORIGINAL | ENCRYPTED | ORIGINAL | ENCRYPTED | (%) | (%) |
|             | HORIZONTAL | VERTICAL | DIAGONAL | HORIZONTAL | VERTICAL | DIAGONAL |  |
| Lena        | 7.4331    | 7.9974    | 0.9455   | 0.9726   | 0.9211   | -0.0007  | 0.0028   | -0.0019  | 99.60  | 33.46  |
| Cameraman   | 7.0097    | 7.9977    | 0.9334   | 0.9592   | 0.9086   | 0.0045   | -0.0019  | 0.00015  | 99.60  | 33.46  |
| Peppers     | 6.9836    | 7.9900    | 0.9809   | 0.9783   | 0.9630   | -0.0022  | 0.0019   | -0.0019  | 99.60  | 33.46  |
| Canoe       | 7.4132    | 7.9940    | 0.7810   | 0.8130   | 0.7301   | 0.0025   | 0.0015   | -0.0016  | 99.60  | 33.46  |
| Tape        | 6.7254    | 7.9973    | 0.9915   | 0.9736   | 0.9697   | -0.0041  | 0.0009   | -0.0058  | 99.60  | 33.46  |

### Table 5. Key Sensitivity Analysis

| Functions with Chaotic Map Initial Parameters | Key Set-1 (Original Set) | Key Set-2 (Underlined Value Changed) |
|-----------------------------------------------|--------------------------|--------------------------------------|
| XOR Function Parameters - K₁                   | Y₁=1.9506457812          | Y₁=1.9506457812                      |
|                                               | Y₂=0.2004547845          | Y₂=0.2004547845                      |
|                                               | Y₃=0.1003695214          | Y₃=0.1003605214                      |
| Dynamic DNA Encoding Parameters - K₂           | Y₁=0.99999994587         | Y₁=0.99999994581                     |
|                                               | Y₂=3.9999993698          | Y₂=3.9999993698                      |
| Composite Chaotic Maps - K₃                   | Y₁=16.1547852365         | Y₁=16.1547852365                     |
|                                               | Y₂=45.9214146983         | Y₂=45.9214146983                     |
|                                               | Y₃=3.9999987412          | Y₃=3.9999987412                      |
|                                               | Y₄=0.0100054756          | Y₄=0.0100054756                      |
|                                               | Y₅=0.9452147836          | Y₅=0.9452147836                      |
|                                               | Y₆=1.40000000001         | Y₆=1.40000000001                     |
|                                               | Y₇=0.30000000001         | Y₇=0.30000000001                     |
|                                               | Y₈=0.4000002111          | Y₈=0.4000002111                      |
|                                               | Y₉=3.9999998634          | Y₉=3.9999998634                      |
|                                               | Y₁₀=0.9999944552         | Y₁₀=0.9999944552                     |
|                                               | Y₁₁=3.9998989899         | Y₁₁=3.9998989899                     |
|                                               | Y₁₂=0.5036000102         | Y₁₂=0.5036000102                     |
|                                               | Y₁₃=0.2030049872         | Y₁₃=0.2030049872                     |
5. CONCLUSION
An Encryption algorithm using Dynamic DNA Encoding and Pixel Scrambling using Composite Chaotic Maps is proposed. Scrambling was done by 8 different chaotic maps where selection of these maps was done by another chaotic map. The diffusion of the pixel values was done dynamic DNA encoding. The DNA encoding was done through XOR of an encoded chaotic map and encoded image pixel values. A separate XOR function with 2 different maps was also embedded after every step. The result analysis showed that two iterations of DNA encoding and pixel scrambling, effectively resists attacks like plaintext, differential, spatial and statistical, making it a secure and capable encryption application.

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