Encrypting Multiple Images With an Enhanced Chaotic Map

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ABSTRACT
A multiple-image encryption scheme based on an enhanced chaotic map is proposed. This scheme combines multiple grayscale images into three planes. An amplified sine map is used to generate a dynamic permutation table and a chaotic sequence. The initial parameters of the amplified sine map are obtained from an elliptic curve coordinate, computing using elliptic curve point multiplication between the input image hash value and the seed value of an elliptic curve. The dynamic permutation table performs cyclic shift transformation on the input image, diffusing it horizontally and vertically. The diffused image is converted to a cipher image through an XOR operation with the chaotic sequence generated by the amplified sine map. Using an amplified sine map provides larger key space, more extensive chaotic range, more extensive control parameters, better sensitive initial values and enhanced security against cryptanalysis. The experiment results indicate that the proposed scheme is fast, secure, efficient and can resist certain cryptographic attacks. Compared to other recent schemes, the proposed scheme is shown to be secure and efficient.

INDEX TERMS
Multiple image encryption, cyclic shift transformation, amplified sine map, elliptic curve cryptography.

I. INTRODUCTION
With the rapid advancement of multimedia technology, developers and researchers have made it extremely simple to transfer multiple data sets simultaneously. As a result, there is a greater need for high-security and faster data communication methods. Image, video, and other multimedia data have high data redundancy and capacity, as well as a high correlation between adjacent pixels. Traditional encryption schemes like Data Encryption Standard (DES), Advanced Encryption Standard (AES), and others are not always efficient enough to encrypt these data. Researchers developed various encryption techniques by using concepts on DNA encoding [1], wavelet transform [2], [3], compressed sensing [4], ELGamal cryptosystem [5], visual secret sharing [6], etc. On the other hand, because of the ergodicity, unpredictability, non-convergence, and high sensitivity to the initial conditions, encryption schemes that are based on chaos-based [7] have piqued the attention of a large number of developers and researchers.

In chaos-based cryptography, two main issues arise (i) one-dimensional (1D) chaotic maps which do not satisfy the unpredictability property, and (ii) high-dimensional (HD) chaotic maps, despite exhibiting complex and chaotic behavior, it requires more computational complexity [8], [9]. This led to the state-of-the-art 1D chaotic map with a simple structure, more extensive chaotic range, better sensitive initial values with low computational complexity.

Mansouri et al. [10] proposed a new sine powered chaotic system. The chaotic map is then used in a new encryption scheme based on row-by-row and column-by-column confusion and diffusion operations. The chaotic system exhibits high randomness and sensitivity, solving the correlation of adjacent pixels. Later, they also proposed a new amplified
1-D chaotic map generator [11], which amplifies the existing 1-D maps. The amplified chaotic map is then used for the generation of initial parameters for the index representation operation. Finally, a bit-level operation is carried out to generate the cipher image.

During the process of encryption using Latin squares [12], the three channels of colour images are encrypted one by one, which results in many redundant operations and low efficiency. Hua et al. [13] developed a colour image encryption scheme using orthogonal Latin squares and a 2D chaotic system that overcomes the weakness of the Latin squares. Further, Hua et al. [14], [15] and proposed a 2D parametric polynomial chaotic system and n-dimensional polynomial chaotic system that possess robust chaos, late chaos degradation and desired dynamic properties with customized parameters for desired Lyapunov exponents for better dynamic properties.

Zhang et al. [16] use DNA encoding and a chaotic system to develop a multiple-image encryption technique. Multiple k images are combined and a combined big image is generated and SHA256 is used on the big image to determine the initial parameter of the chaotic map. The big image is further decomposed into k encrypted images after pixel shuffling with the Piece-wise Linear Chaotic Maps (PWLCM) and DNA decoding. Concerning the encryption process’s speed, Enayatifar et al. [17] developed a multiple-image encryption method based on Index-based permutation-diffusion and DNA sequences. A single big image is created using multiple images, and then converted into a one-dimension array. DNA sequence and cellular automata are employed to make permutation more secure in a quick and effective combined index based permutation and diffusion system.

Zarebnia et al. [18] created a hybrid chaotic systems-based multiple image encryption. In their method, the smaller blocks of plain-images are shuffled using the chaotic system, and permutation is performed. Using the Arnold cat map and cyclic shift operation, the cipher image is obtained using XOR operation. Another PWLCM based multiple-image encryption scheme was proposed by Patro et al. [19]. In their method, multiple grayscale images were combined to create a bigger 2D-image. Row-wise and column-wise permutation is performed to scramble the big image and produce the cipher image through the cross-coupled PWLCM technique. By combining the theory of chaotic system and elliptic curve cryptography (ECC), Singh et al. [20] use hyper-chaotic system with 3D scrambling to develop multiple image encryption. They combine n-images to produce a 3D image and the hyper-chaotic system’s initial parameters are generated using SHA512. The permutation and substitution operations in carried out using the hyper-chaotic system. Finally, the cipher 3D image is formed by conducting a bit-wise XOR operation between the scrambled 3D image and the chaotic 3D image.

Many methods have been proposed to improve 1D chaotic maps’ security levels so they can be used in cryptography applications. The fundamental problem that 1D classical chaotic maps suffer when realized on a digital computer is dynamical degradation. The enhanced methods can be divided into nine categories, cascading multiple chaotic maps [21], perturbing the chaotic states [22], switching between multiple chaotic maps [23], error compensation [24], combining chaotic maps using modular operation [25], coupling chaotic maps [26], introducing delays [27], bit reversal chaotic map [28], and finite state machine [29].

These enhanced methods make use of additional external sources, including multiple chaotic maps, another chaotic map, and pseudo-random numbers, which makes the chaotic map’s structure complex and boosts computational complexity. Our chaotic map can create chaotic points seamlessly without the need for additional mathematical operations. Additionally, our chaotic map can produce high-quality behaviour like security and randomness without the support of an additional external source like a classical chaotic map.

The chaotic image encryption structure’s augmented chaotic maps were applied in various recent proposed image encryption algorithms. In a 1D chaotic map, which is used as a source of entropy, chaotic points are leveraged to encrypt image pixels using the diffusion and confusion fundamental processes. Because initial conditions and control parameters are so sensitive to even tiny changes, the majority of proposed algorithms employ them as secure keys. A chaotic image encryption-based chaotic Jaya optimization technique was developed by the authors of [30] to produce S-boxes. The proposed algorithm employed two encryption operations to accomplish Shannon’s confusion/diffusion characteristics.

A new, improved 1D sinusoidal chaotic system (1DSC), which is the core part of the proposed image encryption, was introduced in [31]. The authors presented new image encryption based on dynamic bit-shifting recombination operation and a non-linear diffusion technique. A novel signcryption system for medical images was proposed by the authors of [32] based on a new chaotic map and a combination strategy of hybrid cryptography techniques. The medical images were encrypted using elliptic curve cryptography. The authors improved the 1D classical chaotic map (Tent map) using a finite state machine, and then utilized the enhanced chaotic map to create a novel image encryption algorithm. The proposed chaotic map’s security is a prerequisite for the proposed algorithm [33].

The proposed method can encrypt twelve secret images with more than the those given in [16], [18], [19], [20], [34], and [36] except for [17], [35], and [37] with any i numbers of images. Theoretically, in [17], [35], and [37], i numbers of images can be given as input. However, a bottleneck can occur with respect to resource constraints in the computing device during actual implementation. Unlike other proposed methods where multiple chaotic systems are used as in [16], [18], [19], and [35] to provide the discrete dynamics of chaos, or that of hyper-chaotic system [20], [37], the proposed method only uses Amplified Sine Map (ASM) to fulfill the discrete dynamics of chaos. With the use of ECC [38], [39]
for key exchange, the proposed method is secure, efficient and robust against various statistical attacks.

The overall contribution of the proposed encryption scheme can be summarized as follows:

1) A multiple grayscale image encryption based on enhanced chaotic map is proposed.
2) To avoid known plain-text attacks and chosen plain-text attacks, SHA384 is adopted to generate the initial conditions of the amplified chaotic system.
3) An amplified Sine map is used, which exhibits complex chaotic behaviour with low computational complexity.
4) A cyclic shift transformation (CST) is introduced where random byte shifts along the horizontal and vertical axes are carried out.
5) The iteration involved in the computation of random sequence used for encryption is reduced by a factor of four using base conversion operation.

The rest of the paper is structured as follows. Section II describes the preliminaries. Section III describes the proposed multiple image encryption method. Section IV displays the simulation. Section V presents the security analysis of the algorithm, followed by the Conclusion in Section VI.

II. PRELIMINARIES

A. CHAOTIC MAP

Initial values and control parameters are extremely important in chaotic maps. Any small variation in the initial conditions results in a significant difference. One-dimensional (1D) and high-dimensional chaotic maps are the two types of chaotic maps. One-dimensional maps usually feature only one or a few variables, as well as a limited output range.

1) SINE MAP

The 1D Sine Map (SM) is define as:

\[ x_{n+1} = \gamma \sin(\pi x_n) \]  

where \( \gamma \in [0, 1] \) is the control parameter and when \( \gamma \in [0.87, 1] \), it manifests chaotic behavior.

2) AMPLIFIED SINE MAP

Unlike the traditional Sine Map, the Amplified Sine Map (ASM) [11] possesses a simple structure, larger chaotic range, bigger control parameters and better sensitive initial values. The Amplified Sine Map is defined as:

\[ x_{n+1} = \frac{\cos(\gamma \delta \pi \sin(\pi x_n))}{\log(3 - \gamma \sin(\pi x_n))} \]

where \( \gamma > 0 \), \( \delta \in [0, 1] \) and \( x_n \in [0, 1] \) is the chaotic system parameter.

The bifurcation diagram of SM and ASM is shown in Fig. 1. The bifurcation diagram is used to visually analyse the chaotic behaviour of a dynamic system. Fig. 1 shows that the ASM exhibit chaotic behaviour over the whole control parameter range, with a wider output range than the SM. The Lyapunov Exponent in Fig. 2 also shows that the ASM exhibit good chaotic behaviour. NIST randomness test is performed and tabulated in Table 1 to test the randomness of the pseudo-random sequence (PRS) generated from ASM.

B. CYCLIC SHIFT TRANSFORMATION (CST)

Cyclic shift transformation (CST) is a method for scrambling image pixels in order to reduce pixel correlation. A dynamic permutation table is generated using a multi chaotic map which helps in performing random byte circular shifts along horizontal and vertical axes. The step size of the shift is based on the index of the permutation table. The structure of CST in the proposed method are as follows:

Step 1: An ASM sequence is generated using Equation 2. The sequence is sorted in ascending order and duplicate elements are removed.

Step 2: A permutation table (P_table) is generated using the values from step 1 whose length is equal \((M_1 + N_1)\), where \(M_1\) and \(N_1\) are the row and column dimension of the combined input image.

Step 3: Row_P – table and Column_P – table are assigned to the combined input image using the values from step 2.

Step 4: If the particular Row_P – table is i, the corresponding row is circular right shifted to i positions. The Circular right shift is performed for all the rows with respect to its Row_P – table value. Similarly, if the particular Column_P – table value is j, the corresponding columns is circular down shifted to j positions. The Circular down shift is performed for all the column with respect to its Column_P – table value.

The above CST process is illustrated in Fig. 3 and Fig. 4 for shift row and shift column respectively. Algorithm 1 represents the pseudo code generated for CST.

C. ELLIPTIC CURVE OPERATIONS

Given an elliptic curve \( E_p : y^2 \equiv x^3 + ax + b \mod p \) and the seed point \( S(x_s, y_s) \). The elliptic curve point \( hS(x_{hs}, y_{hs}) = S + S + S + \ldots + h \) times, \( h \) is an integer. \( hS(x_{hs}, y_{hs}) \) can be computed using Algorithm 2.

The algorithm to compute point addition \((P_3(x_3, y_3) = P_1(x_1, y_1) + P_2(x_2, y_2))\) when \( P_1 \neq P_2 \) or \( P_1 == P_2 \) is shown in Algorithm 3. Point subtraction \((P_3(x_3, y_3) = P_1(x_1, y_1) - P_2(x_2, y_2))\) is converted to point addition by converting the \( y_2 \) coordinate to negative as \((P_3(x_3, y_3) = P_1(x_1, y_1) + P_2(x_2, -y_2))\).

III. PROPOSED MULTIPLE IMAGE ENCRYPTION

The proposed multiple image encryption is as follows:

A. KEY GENERATION

The key generation of the proposed method is as follows:

Step 1: Combine all the input grayscale images into three planes of equal size and obtain a colour image \( I_1 \).
Step 2: Compute SHA-348 on $I_1$ to generate a 384-bit hash value ($h$).

Step 3: Compute $hS(x_{hS}, y_{hS})$ by performing an elliptic curve point multiplication between ($h$) and elliptic curve seed $S(x_s, y_s)$.

Step 4: Binarize $x_{hS}$ and $y_{hS}$ into 384 bits each and store as $bin_x$ and $bin_y$ respectively.

Step 5: Divide the 384-bits in $bin_x$ and $bin_y$ into three groups each of 128 bits and denote as $hS_1, hS_2, hS_3, hS_4, hS_5$ and $hS_6$.

Step 6: Generate the keys as:

$$x_{n1} = \frac{\text{BaseConvert}[hS_1, 2]}{2^{128}}$$  \hspace{1cm} (3)$$

$$\delta_1 = \frac{\text{BaseConvert}[hS_2, 2]}{2^{128}}$$  \hspace{1cm} (4)$$

$$\gamma_1 = 2200 + \frac{\text{BaseConvert}[hS_3, 2]}{2^{116}}$$  \hspace{1cm} (5)$$

$$x_{n2} = \frac{\text{BaseConvert}[hS_4, 2]}{2^{128}}$$  \hspace{1cm} (6)$$

where, $x_{n1}, \gamma_1$ and $\delta_1$ will be used as the keys for the permutation table of the CST. $x_{n2}, \gamma_2$ and $\delta_2$ will be used as the keys for generating a pseudo-random sequence $PRS$. $\text{BaseConvert}[\text{list, } b]$ converts the value of the list with respect to base $b$.

**B. ENCRYPTION PROCESS**

The encryption process is carried out as shown in the algorithm 4 and discussed below.

Step 1: Combine all the input grayscale images into three planes of equal size and obtain a colour image $I_1$.

Step 2: Perform CST on all the three planes of $I_1$ using algorithm 1 and the keys $x_{n1}, \gamma_1$ and $\delta_1$.

Step 3: Using Equation 2 along with the keys $x_{n2}, \gamma_2$ and $\delta_2$ generate a pseudo-random sequence $PRS$ of length ($M_1 \times N_1 \times 3/4$), where ($M_1 \times N_1$) is the dimension of $I_1$.

Step 4: Compute $|ASM[i] \times 10^{16}|$ and base convert it using 256 as base up to eight terms and pick the elements at position three to six and store in $PSR$.

Step 5: Perform $\text{XoR}$ operation between the values of Step 2 and $PRS$.

Step 6: Generate the cipher image.

**C. KEY SHARING**

The initial parameters $x_{n1}, \gamma_1, \delta_1, x_{n2}, \gamma_2$ and $\delta_2$ are all generated from $h.S(x_{hS}, y_{hS})$. In order to decrypt the images exactly as the original images, the same set of initial parameters are required in the receiver side. $h.S(x_{hS}, y_{hS})$ is secretly shared as $h.S'(x'_{hS}, y'_{hS})$ to the communicating party. $h.S'(x'_{hS}, y'_{hS})$ is computed as:

$$h.S' = [r.S, (h.S + r.R)]$$  \hspace{1cm} (9)
TABLE 1. Randomness Test on sequence generated from ASM.

| Test                      | $p$-value | $P_{RS1}$ | $P_{RS2}$ | $P_{RS3}$ | $P_{RS4}$ | $P_{RS5}$ |
|---------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\text{Monobit Test}$     | 0.11023   | 0.165318  | 0.729901  | 0.680752  |           |           |
| $\text{Frequency within Block}$ | 0.072604  | 0.866317  | 0.360072  | 0.078537  |           |           |
| $\text{Runs Test}$        | 0.483461  | 0.277409  | 0.684825  | 0.635841  |           |           |
| $\text{Longest Run of Ones in a Block}$ | 0.876549  | 0.665436  | 0.798973  | 0.330148  |           |           |
| $\text{Binary Matrix Rank}$ | 0.769933  | 0.843884  | 0.211151  | 0.685974  |           |           |
| $\text{PDFT}$             | 0.027444  | 0.166032  | 0.060573  | 0.674394  |           |           |
| $\text{Non-Overlapping Template Matching}$ | 0.902773  | 0.748860  | 0.184214  | 0.632401  |           |           |
| $\text{Overlapping Template Matching}$ | 0.113538  | 0.729445  | 0.816368  | 0.533173  |           |           |
| $\text{Maurer's Test}$    | 0.340917  | 0.341394  | 0.341477  | 0.341314  |           |           |
| $\text{Linear Complexity}$ | 0.963107  | 0.715299  | 0.654654  | 0.783117  |           |           |

where,

- $r$ is a random integer
- $R$ public of the receiver.
- $R = key \cdot S$
- key is the private key of the receiver.

The receiver gets $(h \cdot S(x_{hS}, y_{hS}))$ from $h \cdot S(x'_{hS}, y_{hS})'$ by using Equation 10

$$h \cdot S = (h \cdot S + r \cdot R) - key \cdot r \cdot S$$

D. DECRYPTION PROCESS

Using Equation 10, the receiver computes $(h \cdot S(x_{hS}, y_{hS}))$ from $h \cdot S(x'_{hS}, y_{hS})'$ using his/her private key $key$. The initial parameters $x_{n1}$, $y_{1}$, $\delta_1$, $x_{n2}$, $y_2$ and $\delta_2$ are generated from the shared key $(h \cdot S(x_{hS}, y_{hS}))$ using Step 4 to Step 6 given in III-A.

The decryption process of the proposed method is as follows:

Step 1: Using Equation 2 along with the keys $x_{n2}$, $y_2$ and $\delta_2$ generate a pseudorandom sequence $PRS$ of length $(M_1 \times N_1 \times 3)$, where $(M_1 \times N_1)$ is the dimension of $C_1$.

Step 2: Perform XoR operation between $PRS$ and the three planes of $C_1$.

Step 3: Perform reverse CST on the three planes of step 2 using the permutation table the keys $x_{n1}$, $y_1$, $\delta_1$.

Step 4: Separate the three planes of Step 3.

Step 5: Extract all the plain images from Step 4.

IV. SIMULATIONS

The proposed multiple grayscale image encryption is simulated using Wolfram Mathematica 13 on a Fujitsu Celsius Workstation with Intel Xeon(R) W-2133 @ 3.60 GHz and
a ram of 32GB. The experimental images were downloaded from the USC-SIPI database [40]. In this paper, due to space limitations, we used 12 (twelve) images to form a single combined RGB image ($C_{I}$). Each plane of the RGB is composed of 4 (four) grayscale images. Experimental analysis are carried out on four combine images- $C_{I-1}$, $C_{I-2}$, $C_{I-3}$ and $C_{I-4}$. The image representation of $C_{I-1}$, $C_{I-2}$, $C_{I-3}$ and $C_{I-4}$ are shown in the Fig. (6a, 6c, 6e and 6g) respectively. The images used in combine images- $C_{I-1}$, $C_{I-2}$, $C_{I-3}$, $C_{I-4}$ and its respective planes are shown in Table 2. The proposed method can encrypt and decrypt the multiple grayscale images successfully.

V. SECURITY ANALYSIS

A. PSNR AND SSIM

The peak-signal-to-noise-ratio (PSNR) and structural-similarity-index (SSIM) are used to ascertain the accuracy of the image after the decryption. The computed values are shown in Table 3. The PSNR and SSIM are calculated using the below formula:

$$PSNR = 20 \times \log_{10} \frac{Max_{P\text{value}}}{\text{Mean}_{\text{error}}}$$  \hspace{1cm} (11)$$

$$\text{Mean}_{\text{error}} = \frac{1}{M_{1} \times N_{1}} \sum_{i=0}^{M_{1}-1} \sum_{j=0}^{N_{1}-1} (O_{img}(i,j) - D_{img}(i,j))^{2}$$  \hspace{1cm} (12)$$

where $Max_{P\text{value}}$: maximum supported pixel value. $\text{Mean}_{\text{error}}$: mean squared error. $M_{1} \times N_{1}$: dimension of the image. $O_{img}(i,j)$: original image pixel value at index $(i,j)$. $D_{img}(i,j)$: decrypted image pixel value at index $(i,j)$.

$$\text{SSIM}(x, y) = \frac{(2M_{x}^{y} M_{y}^{x} + c_{y}) (2\text{Cov}_{x}^{y} + c'_{x})}{((M_{x}^{y})^{2} + (M_{y}^{x})^{2} + c_{x}) ((S_{x}^{y})^{2} + (S_{y}^{x})^{2} + c'_{x})}$$  \hspace{1cm} (13)$$

where $M_{x}^{y}$ = mean value of $x$, $M_{y}^{x}$ = mean value of $y$. $S_{x}^{y}$ = standard deviation value of $x$. $S_{y}^{x}$ = standard deviation value of $y$. $\text{Cov}_{x}^{y}$ = covariance value of $x$ and $y$. $c_{x} = (k_{x}L_{x})^{2}$ and $c'_{x} = (k'_{x}L_{x})^{2}$. $k_{x} = 0.01$ and $k'_{x} = 0.03$. $L_{x} = 2^{\text{count}} - 1$. $\text{count}$= no. of bit per pixel.

B. KEY SPACE

A key space is the total number of all the possible keys for a given encryption scheme. The key space in an ideal encryption technique should be large enough to resist a brute force attack. The keys used in the proposed method are
(x_n1, y_1, δ_1, x_n2, y_2, δ_2). As a result, the suggested enhanced encryption scheme’s total key space is 2^{332} (approx). The value is sufficiently big to overcome any type of brute force attack.

C. HISTOGRAM ANALYSIS
An image histogram is an analysis of the statistical attack which is shown graphically by plotting the frequency. The frequency is the plot on every pixel value across all the pixel values possible. The histogram of a plain image shows uneven pixel frequency distribution while the histogram of a well decrypted image shows equal pixel frequency distribution. Fig. (6a, 6b, 6c, 6d) and (6e, 6f, 6g, 6h) shows the plane images and the cipher images. Fig. (7a, 7b, 7c, 7d) and (7e, 7f, 7g, 7h) represents the histogram of the plane images and histogram of the cipher images.

D. COMPLEXITY OF THE PROPOSED METHOD
The computational complexity of the proposed method can be summarised as:

1) The time complexity of generating the ASM sequence for the permutation table is O(3 × (M_1 + N_1)).
2) The time complexity of performing the CST operation on the three planes is O(3 × (M_1 + N_1)).
3) The time complexity of generating the chaotic sequence PSR is O(3 × M_1 × N_1).
4) The time complexity of performing a bit-XOR operation on two n-bit value is O(n) and each values are represented by 8-bits. So, the time complexity of performing bit-XOR operation in between CST[T_1] and PSR is O(8 × 3 × M_1 × N_1)

The overall time complexity to execute the encryption procedure is O(3 × (M_1 + N_1)) + O(3 × (M_1 + N_1)) + O(3 × M_1 × N_1) + O(8 × 3 × M_1 × N_1) = O(27M_1N_1) + O(6(M_1 + N_1))

E. INFORMATION ENTROPY ANALYSIS
The information entropy analyses how the image has randomness in it by computing:

\[ E_p(\chi) = - \sum_{i=1}^{n} P_b(\chi_i) \log_\beta P_b(\chi_i) \]  \hspace{1cm} (14)

where \( E_p(\chi) \): entropy. \( P_b(\chi_i) \) : probability mass function. \( \beta = 2 \). The entropy value is shown in Table 4 which is computed using equation 14 on the cipher images. A Comparison of the entropy with the other state of the art methods is tabulated in Table 10.

F. AVALANCHE EFFECT
The Avalanche effect is an idea related to the specific behaviour of the arithmetic function used in encryption. It states that “a minor variation in plain text can impact a substantial variation in the cipher text”. As a result, it’s one of the processes to check for desirable qualities of the cipher image. An effective encryption technique is predicted to be good if the value of the avalanche is very near to 50 percent. For the suggested approach, the avalanche value for the cipher image Fig. (8b, 8e, 8h, 8k) generated by the plain image Fig. (8a, 8d, 8g, 8j) and the cipher image Fig. (8c, 8f, 8i, 8l) derived by some minor variation in the pixel value of plain image Fig. (8a, 8d, 8g, 8j) is shown in the Table 5.
**Algorithm 1:** The Process of CST

**Input:** INPUT IMAGE $I_1$, image size $M_1 \times N_1$, ASM initial parameters $(x_{n1}, y_{11}, \delta_1)$

**Output:** CST IMAGE, image size $M_1 \times N_1$

1. for $i \leftarrow 1$ to $M_1 + N_1$ do
2.     Generate ASM[$i$]
3.     $i++$
4. end for
5. Seq$_x$ = ASM[[1; $M_1$]]
6. Seq$_y$ = ASM[[1; $N_1$]]
7. Sort$_x$ = Sort(Seq$_x$)
8. Sort$_y$ = Sort(Seq$_y$)
9. for $i \leftarrow 1$ to Length(Seq$_x$) do
10.     Row$_P$ – table[$i$] = Position of Sort$_x$[$i$] in Seq$_x$
11.     $i++$
12. end for
13. for $i \leftarrow 1$ to Length(Seq$_y$) do
14.     Column$_P$ – table[$i$] = Position of Sort$_y$[$i$] in Seq$_y$
15.     $i++$
16. end for
17. for $i \leftarrow 1$ to Row$_P$ – table[$i$] do
18.     RotateRight, Row[$i$] of $I_1$ by Row$_P$ – table[$i$] position
19.     $i++$
20. end for
21. for $i \leftarrow 1$ to Column$_P$ – table[$i$] do
22.     RotateDown, Column[$i$] of $I_1$ by Column$_P$ – table[$i$] position
23.     $i++$
24. end for

**Algorithm 2:** Elliptic Curve Point multiplication($\cdot$)

**Input:** $a, b, p, S(x_1, y_1), h$

**Output:** $hS(x_{hS}, y_{hS})$

1. Start with $n = h, P_1 = \infty, P_2 = S$
2. while ($n \neq 0$) do
3.     if ($n$ mod 2 === 0) then
4.         $n = n/2$
5.         $P_1 = P_1$
6.         $P_2 = P_2 + P_2$
7.     end if
8.     else
9.         $n = n – 1$
10.        $P_1 = P_1 + P_2$
11.        $P_2 = P_2$
12.     end if
13. end while
14. if ($n == 0$) then
15.     $P_1 = hS(x_{hS}, y_{hS})$
16. end if

**Algorithm 3:** Elliptic Curve Point addition($+$)

**Input:** $a, b, p, P_1(x_1, y_1), P_2(x_2, y_2)$

**Output:** $P_3(x_3, y_3)$

1. if ($P_1(x_1, y_1) \neq P_2(x_2, y_2)$) then
2.     $\lambda = \frac{y_2 - y_1}{x_2 - x_1} \mod p$
3.     $x_3 = \lambda^2 - x_1 - x_2 \mod p$
4.     $y_3 = \lambda(x_1 - x_3) - y_1 \mod p$
5. end if
6. else if ($P_1(x_1, y_1) == P_2(x_2, y_2)$) then
7.     $\lambda = \frac{3x_1^2 + a}{2y_1} \mod p$
8.     $x_3 = \lambda^2 - 2x_1 \mod p$
9.     $y_3 = \lambda(x_1 - x_3) - y_1 \mod p$
10. end if

**G. OCCLUSION ATTACK**

Occluded data occurs because of the lack of security in the channel while transferring the encrypted image to the receiver. In our analysis the cipher image generated were occluded 6.5%, 12.5%, 25% and 50%. The occluded cipher images were performed decryption process. The results of
the occlusion attack are represented in Fig. 8, which is identifiable with some pixels lost. The PSNR value of the occluded images was calculated with the original image and the decrypted image. The values were tabulated in the Table 6.

H. KEY SENSITIVITY
An ideal cryptographic scheme should have good key sensitivity. A slight change in the key should completely alter the output of the cryptographic scheme. Fig. 8 shows the output using the original key and by altering one bit of data in the original key.

I. DIFFERENTIAL ATTACKS
In order to prevent the differential attack, the cipher image $C_{img1}$ and the cipher image $C_{img2}$ derived by some minor variation in the pixel value of the plain image. They both should be random enough that the pixel index should not be similar. Two methods to estimate the intensity of a differential attack are the Number of Pixel Changes (NPCR) and the Unified Averaged Changed Intensity (UACI). The theoretically ideal value of NPCR and UACI should be closed to 100% and 33.3% [42] respectively. The rate of pixel change of the cipher
TABLE 2. Image file used in C\textsubscript{1-1}, C\textsubscript{1-2}, C\textsubscript{1-3}, C\textsubscript{1-4} and its respective planes.

| Plane-1 | Plane-2 | Plane-3 |
|---------|---------|---------|
| C\textsubscript{1-1} | Elaine | Jelly beans | Airplane |
|         | Mandrill | Resolution chart | Aerial |
|         | Boat | 21 level step wedge | Stream and bridge |
|         | Couple | Testpat.1k | Tank |
| C\textsubscript{1-2} | Female | Jelly beans | Moon surface |
|         | House | Clock | Aerial |
|         | Peppers | Male | Airplane (U-2) |
|         | Airplane (F-16) | Tree | Car and APCs |
| C\textsubscript{1-3} | Female | Splash | Chemical plant |
|         | Sailboat on lake | Lena | Airplane |
|         | House | Female | APC |
|         | Taxi roof | Aerial | Tank |
| C\textsubscript{1-4} | San Francisco and Oakland | USC texture mosaic #2 | Truck |
|         | Walter Cronkite, frame 7 | Brodatz - Brick wall (D94) | San Diego (Downtown) |
|         | Tiffany | Brodatz - Raffia (D84 I.E.) | Chemical Plant (close view), frame 12 |
|         | Airport | USC texture mosaic #3 (info) | Truck and APCs |

TABLE 3. PSNR and SSIM values of encrypted and decrypted image.

| Image ID | ENCRYPTED | RGB Generated Image |
|----------|------------|---------------------|
|         | PSNR       |                     |
| C\textsubscript{1-1} | 9.48398   | 7.10247             | 8.94423  |
| C\textsubscript{1-2} | 8.56415   | 7.96293             | 8.60384  |
| C\textsubscript{1-3} | 9.05205   | 9.13934             | 9.78612  |
| C\textsubscript{1-4} | 8.09153   | 8.17246             | 9.38841  |

| SISM     |                     |
|----------|---------------------|
| C\textsubscript{1-1} | 0.004886  | 0.008521  | 0.007757  | 0.007121  |
| C\textsubscript{1-2} | 0.004446  | 0.004854  | 0.005617  | 0.005047  |
| C\textsubscript{1-3} | 0.008361  | 0.009821  | 0.009357  | 0.007624  |
| C\textsubscript{1-4} | 0.004222  | 0.006217  | 0.005978  | 0.005562  |

TABLE 4. Entropy values for plane image and encrypted images.

| Image ID | ENTROPY ANALYSIS | RGB Generated Image |
|----------|-------------------|---------------------|
|         | PLANE IMAGE       |                     |
| C\textsubscript{1-1} | 7.4114  | 6.0631  | 7.4320  | 7.3769  |
| C\textsubscript{1-2} | 7.66142 | 7.5632  | 7.2816  | 7.7757  |
| C\textsubscript{1-3} | 7.4292  | 7.6193  | 7.2586  | 7.5964  |
| C\textsubscript{1-4} | 7.7714  | 6.5995  | 7.4751  | 7.6119  |

| ENCRYPTED IMAGE |                     |
|----------------|---------------------|
| C\textsubscript{1-1} | 7.9993  | 7.9993  | 7.9993  | 7.9993  |
| C\textsubscript{1-2} | 7.9992  | 7.9992  | 7.9993  | 7.9998  |
| C\textsubscript{1-3} | 7.9992  | 7.9993  | 7.9993  | 7.9998  |
| C\textsubscript{1-4} | 7.9993  | 7.9992  | 7.9994  | 7.9997  |

TABLE 5. Avalanche value for cipher image on 1 bit changed in plain image.

| AVALANCHE EFFECT |                     |
|-----------------|---------------------|
| Input Image     | Cipher Image 1 bit changed Cipher Image | Avalanche value |
| Fig. 8a | Fig. 8b | Fig. 8c | 50.0051 |
| Fig. 8d | Fig. 8e | Fig. 8f | 50.0452 |
| Fig. 8g | Fig. 8h | Fig. 8i | 50.0052 |
| Fig. 8j | Fig. 8k | Fig. 8l | 50.0060 |

images $C_{mg1}$ and $C_{mg2}$ is measured by NPCR:

$$NPCR_1 = \frac{1}{M_1 \times N_1} \times \sum_{i,j} D_1(i, j) \times 100$$  \hspace{1cm} (15)$$

The average variation of the intensity between original image and cipher image is measured by UACI using the below expression.

$$UACI_1 = \frac{1}{M_1 \times N_1} \left[ \sum_{i,j} \left| C_{mg1}(i, j) - C_{mg2}(i, j) \right| \right]$$  \hspace{1cm} (16)$$

where, $NPCR_1$ represents the NPCR and $UACI_1$ represents UACI of the 512-grayscale image. The size of the images is represented by $M_1 \times N_1$, $L_1$ represents the largest pixel that can be supported and $D_1(i, j)$ is represented by the below expression.

$$D_1(i, j) = \begin{cases} \ 0 & \text{if } C_{mg1}(i, j) = C_{mg2}(i, j) \\ \ 1 & \text{if } C_{mg1}(i, j) \neq C_{mg2}(i, j) \end{cases}$$  \hspace{1cm} (17)$$

The value for NPCR and UACI on four different images i.e in the Fig. (6a, 6c, 6e, 6g) is shown in the Table 7. The NPCR and
TABLE 6. PSNR and SSIM values of occluded image.

| Occluded | DECRYPTED | PSNR | SSIM |
|----------|-----------|------|------|
|          | Plane-1 | Plane-2 | Plane-3 | RGB Generated Image |
| 6.5%     | 21.5367 | 19.2475 | 21.0487 | 20.4953 |
| 12.5%    | 18.5321 | 16.1732 | 17.9929 | 17.4446 |
| 25%      | 15.5407 | 13.1602 | 15.0030 | 14.4440 |
| 50%      | 12.5158 | 10.1017 | 11.9643 | 11.4000 |

TABLE 7. Result of the proposed approach for NPCR and UACI taken on four sets of images.

| Image ID | NPCR and UACI | NPCR | UACI |
|----------|---------------|------|------|
|          | Plane-1 | Plane-2 | Plane-3 | RGB Generated Image |
| CI-1     | 99.6235 | 99.5976 | 99.6037 | 99.6086 |
| CI-2     | 99.6098 | 99.6223 | 99.6040 | 99.6120 |
| CI-3     | 99.5945 | 99.6052 | 99.6067 | 99.6021 |
| CI-4     | 99.5964 | 99.5983 | 99.5918 | 99.5955 |

UACI comparison with other proposed methods are tabulated in Table 10.

J. CORRELATION ANALYSIS
The correlation of an image is computed as:

\[
\text{Correlation} [vec_1, vec_2] = \frac{\text{Covariance} [vec_1, vec_2]}{\rho [vec_1] \times \rho [vec_2]} \tag{18}
\]

Here, Covariance is the covariance. \(\rho\) is the standard deviation. \(vec_1\) and \(vec_2\) are the input vectors.

The orientation of the horizontal, vertical and diagonal which is denoted by \(H_{\text{tal}}, V_{\text{cal}}\) and \(D_{\text{nat}}\) of Plane-1, Plane-2, Plane-3 and the generated RGB image correlation coefficient is shown in Table 8. The correlation coefficient along the \(H_{\text{tal}}, V_{\text{cal}}\) and \(D_{\text{nat}}\) direction of RGB generated plain image and cipher image is plotted by computing with 10000 random pixel values as shown in Fig. 10.

K. RANDOMNESS ANALYSIS FOR ENCRYPTED IMAGES
The randomness of the cipher is checked by performing the NIST test on the cipher image. The proposed approach uses the NIST test to analyze the randomness of the generated cipher image. The NIST test is proposed by Andrew et al. [41] and it consists of 15 different tests. For each and every test p-value are calculated. A cipher image is considered to be random if the p-value is more than 0.01. The NIST test is performed on the cipher images shown in Fig. (8b, 8e, 8h, 8k) using the proposed encryption method and Table 9 shows the result of the test.

L. ATTACK ANALYSIS
The proposed method has got a vast keyspace. So, when an adversary has only cipher-text information, the proposed method will withstand the exhaustive key attack. The proposed method can also withstand Known plain-text attacks. The initial keys for the enhanced chaotic map are derived from the Secure Hash Algorithm’s hash value. So every different image that may differ just by one bit also generates a different hash value leading to different initial values for the enhanced chaotic map.

M. COMPARISON AND DISCUSSION
The proposed multiple image encryption scheme is compared with some of the recent related works [16], [17], [18], [19], [20], [34], [35], [36], [37] that encrypts multiple images where each image is of image dimension 512 \(\times\) 512. The comparison is made with respect to correlation, NPCR, UACI, Entropy, Key-space, Number of images encrypted per execution and execution time of encryption per image as tabulated in Table 10.
FIGURE 9. (a, e, i, m) Occluded cipher images with 6.25%, 12.5%, 25% and 50% occlusion. (b, f, j, n) Decrypted Plane-1, (c, g, k, o) Decrypted Plane-2 and (d, h, l, p) Decrypted Plane-3 of occluded cipher images.

TABLE 8. Correlation coefficient for plane image and encrypted images.

| Image ID | PLANE IMAGE | ENCRYPTED IMAGE |
|----------|-------------|-----------------|
|          | Orientation | Plane-1 | Plane-2 | Plane-3 | RGB Generated Image | Plane-1 | Plane-2 | Plane-3 | RGB Generated Image |
| C₁₋₁     | $H_{ref}$   | 0.909781 | 0.936636 | 0.930746 | 0.934057 | -0.012385 | 0.008586 | -0.001810 | 0.000425 |
|          | $V_{ref}$   | 0.889481 | 0.937112 | 0.902513 | 0.934057 | 0.006438 | 0.012843 | 0.006502 | 0.005525 |
|          | $D_{ref}$   | 0.835325 | 0.885604 | 0.865775 | 0.884037 | -0.019161 | 0.002223 | -0.006094 | -0.002245 |
| C₁₋₂     | $H_{ref}$   | 0.972168 | 0.965771 | 0.964949 | 0.969488 | -0.003857 | -0.001560 | 0.000335 | 0.000320 |
|          | $V_{ref}$   | 0.971038 | 0.962514 | 0.953313 | 0.967228 | -0.011751 | -0.008611 | -0.006261 | -0.007152 |
|          | $D_{ref}$   | 0.948791 | 0.935795 | 0.925495 | 0.943163 | 0.003872 | -0.003285 | 0.008005 | 0.001648 |
| C₁₋₃     | $H_{ref}$   | 0.954617 | 0.937343 | 0.955608 | 0.956955 | -0.003945 | 0.006344 | 0.010601 | 0.001667 |
|          | $V_{ref}$   | 0.929687 | 0.950617 | 0.953111 | 0.947382 | -0.004951 | 0.002170 | -0.005767 | -0.002069 |
|          | $D_{ref}$   | 0.902684 | 0.898827 | 0.925674 | 0.919395 | -0.012216 | 0.015475 | -0.003444 | -0.005128 |
| C₁₋₄     | $H_{ref}$   | 0.973644 | 0.871123 | 0.948498 | 0.930578 | 0.001790 | -0.000849 | -0.015010 | 0.012250 |
|          | $V_{ref}$   | 0.980256 | 0.845536 | 0.931035 | 0.919622 | -0.016426 | -0.002640 | 0.006814 | -0.004834 |
|          | $D_{ref}$   | 0.962030 | 0.774278 | 0.899960 | 0.878867 | -0.005515 | 0.001313 | 0.000736 | -0.004180 |
TABLE 9. Randomness Test.

| Test                                      | p-value     |
|-------------------------------------------|-------------|
| $p_{Monobit\_Test}$                      | 0.228584    |
| $p_{Frequency\_within\_Block}$           | 0.069345    |
| $p_{The\_Runs\_test}$                    | 0.446026    |
| $p_{Longest\_Run\_of\_Ones\_in\_a\_Block}$ | 0.292414    |
| $p_{Binary\_Matrix\_Rank}$               | 0.762835    |
| $p_{DPT}$                                 | 0.027444    |
| $p_{Non\_Overlapping\_Template\_Matching}$ | 0.361925    |
| $p_{Overlapping\_Template\_Matching}$    | 0.231136    |
| $p_{Maurer's\_Test}$                     | 0.341355    |
| $p_{The\_Linear\_Complexity}$            | 0.565642    |
| $p_{The\_Serial\_Test}$                  | 0.219754    |
| $p_{Sequential\_Test}$                   | 0.774005    |
| $p_{Approximate\_Entropy}$               | 0.580378    |
| $p_{Cumulative\_Sum\_Test}$              | 0.289672    |
| Random\_excursions\(_RE\)                | 0.672276    |
| $p_{\mu=4}$                              | 0.897589    |
| $p_{\mu=3}$                              | 0.101820    |
| $p_{\mu=2}$                              | 0.217747    |
| $p_{\mu=1}$                              | 0.893072    |
| $p_{\mu=1}$                              | 0.522128    |
| $p_{\mu=2}$                              | 0.225867    |
| $p_{\mu=3}$                              | 0.529444    |
| $p_{\mu=4}$                              | 0.469220    |
| $p_{\mu=9}$                              | 0.730301    |
| $p_{\mu=8}$                              | 0.926899    |
| $p_{\mu=7}$                              | 0.874706    |
| $p_{\mu=6}$                              | 0.780858    |
| $p_{\mu=5}$                              | 0.831170    |
| $p_{\mu=4}$                              | 0.747203    |
| $p_{\mu=3}$                              | 0.726637    |
| $p_{\mu=2}$                              | 0.606935    |
| $p_{\mu=1}$                              | 0.669815    |
| $p_{\mu=1}$                              | 0.319767    |
| $p_{\mu=2}$                              | 0.267938    |
| $p_{\mu=3}$                              | 0.171741    |
| $p_{\mu=4}$                              | 0.107039    |
| $p_{\mu=5}$                              | 0.169454    |
| $p_{\mu=6}$                              | 0.415505    |
| $p_{\mu=7}$                              | 0.596601    |
| $p_{\mu=8}$                              | 0.475222    |
| $p_{\mu=9}$                              | 0.408044    |

With respect to statistical analyses such as correlation (horizontal, vertical, diagonal), NPCR, UACI and entropy, all the compared related works in [16], [17], [18], [19], [20], [34], [35], [36], and [37] show a comparable result. For a good cipher image, the correlation coefficients are expected to have a value close to zero, indicating a weak correlation between the pixels in the cipher image. The proposed and compared methods can generate a low correlated cipher image. The NPCR and UACI data indicate that the proposed and compared methods can resist differential attacks. With eight bits representing each pixel of the cipher image, the maximum entropy value is eight. The proposed and compared methods can generate an entropy value of nearly eight. The key space for all the compared related work is large enough to resist Brute force attack with [18] having the maximum of $2^{648}$ and [17] having the maximum of $2^{128}$. The proposed method has a moderate key space of $2^{352}$. The claimed key space of [34] is $2^{628}$, which consists of eight initial parameters derived from the hash value of SHA-256 applied on the input images with a precision of $10^{14}$ and a set of fixed eight external parameters ($c_1, c_2, \ldots, c_8$). As the external parameters are fixed and the initial parameters of the chaotic system are derived from the hash value of SHA-256, the actual key-space is $2^{256}$. The proposed method can encipher twelve secret images which is more than the those given in [16], [18], [19], [20], [34], and [36] except for [17], [35], and [37] with any $i$ numbers of images. Theoretically, in [17], [35], and [37], $i$ numbers of images can be given as input. However,
TABLE 10. Comparison.

| Scheme        | Horizontal Correlation | Vertical Correlation | Diagonal Correlation | NPCR | UACI | Entropy | Key space | Number of images | Encryption time/image (sec.) |
|---------------|------------------------|----------------------|----------------------|------|------|---------|-----------|------------------|-----------------------------|
| Ref. [16]     | -0.0019                | -0.0066              | 0.0031               | 99.61% | 33.45% | 7.9993  | $2^{286}$  | 4                | 43                          |
| Ref. [17]     | 0.0016                 | 0.0022               | 0.0007               | 99.61% | 33.57% | 7.9992  | $2^{128}$  | $i^2, i \in \mathbb{Z}$ | 0.04                        |
| Ref. [18]     | -0.0036                | 0.0026               | 0.0012               | 99.59% | 33.48% | 7.9995  | $2^{648}$  | 4                | 0.24                       |
| Ref. [19]     | -0.0020                | -0.0047              | 0.0028               | 99.61% | 33.47% | 7.9993  | $1.24 \times 2^{237}$ | 4                | 0.32                       |
| Ref. [20]     | -0.0036                | 0.0016               | -0.0058              | 99.61% | 33.48% | 7.9999  | $2^{512}$  | 8                | 0.07                       |
| Ref. [34]     | -0.0003                | 0.0011               | 0.0013               | 99.60% | 33.51% | 7.9998  | $2^{628}$  | 4                | 0.42                       |
| Ref. [35]     | 0.0023                 | 0.0052               | 0.0024               | 99.61% | 33.47% | 7.9996  | $1.15 \times 2^{674}$ | $i^2, i \in \mathbb{Z}$ | 2.46                       |
| Ref. [36]     | 0.0015                 | -0.0002              | -0.0004              | 99.60% | 33.48% | 7.9998  | $2^{128}$  | 9                | 0.55                       |
| Ref. [37]     | 0.0013                 | -0.0009              | -0.0023              | 99.62% | 33.46% | 7.9999  | $2^{478}$  | $i, i \in \mathbb{Z}$ | 2.42                       |
| Proposed      | 0.0024                 | 0.0055               | -0.0022              | 99.62% | 33.42% | 7.9998  | $2^{332}$  | 12               | 0.25                       |

a bottleneck can occur with respect to resource constraints in the computing device during actual implementation. The proposed method has a decent execution speed, faster than most of the compared methods. The proposed method can decipher the exact original images from the cipher images, while the method given in [36] provides visually similar images but not the exact original images. For the proposed method, the PSNR and SSIM value are $\infty$ and one, respectively, while for [36], the PSNR is in the range of 25 to 33 and SSIM is in the range of 0.89 to 0.97. The proposed method has the edge over other methods in reducing the iteration of a chaotic system. If $M_1 \times N_1$ is the size of the image, the proposed method reduces the iteration in the chaotic system by a factor of four by employing a base conversion operation. In contrast, the compared methods iterate for $M_1 \times N_1$ to generate the chaotic sequence. The keys used for the proposed method are securely shared as an elliptic curve point as given in Section III-C. The keys are safe from the adversary as the elliptic curve discrete logarithmic problem is one of the complicated problems that cannot be solved in a feasible time as of now.

VI. CONCLUSION

This paper proposed a multiple images encryption scheme based on an amplified Sine map. The ASM exhibits complex chaotic behaviour with a more extensive chaotic range and low computational cost. Two different key sets of the ASM are generated by using SHA384. A dynamic permutation table is generated for the CST using the first key set of ASM. The CST then performs random byte circular shifts along the horizontal and vertical axes of the combined input image. Again, using the second key set of ASM, a chaotic image is generated whose dimension is equal to that of the input combined image. Bitwise Xor is performed between
consideration. The experimental analysis and results show the effectiveness of the proposed method against various cryptographic attacks. The performance analysis shows that the proposed algorithm is superior or on par with the other methods under consideration.

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