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A novel approach for augmenting encryption security by the utilization of dominator coloring in Latin square graphs

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Abstract

In this expansive world of extensive communication, privacy plays a pivotal role. With the intrusion and technological invasion growing up, there is always a need to keep enhancing the security level of the data shared. The vast domain of cryptography comprises numerous encryption algorithms that have recently gained popularity with the communication networks. As the awareness has increased, technologists are actively striving to innovate newer and more robust encryption techniques to address this challenge. Mathematics provides the theoretical basis for the design and analysis of cryptographic systems, by ensuring the confidentiality, integrity, and authenticity of shared data in the digital world. Graph Theory, in particular, studies the combinatorial aspects of the proposed algorithm, thereby reinforcing the underlying structure. In this article, we intend to utilize the characteristics of Latin squares and their related graphs in conjunction with the dominator coloring. This application is hoped to resolve the existing problems faced by the cryptographers and the cryptologists while also presenting a new mathematical encryption system thereby intensifying the security level of the shared information.

Keywords and phrases: Cryptography, encryption, Latin square, dominator coloring.
2020 AMS Subject Classification: 30E10, 41A10, 41A25, 46E30.

1 Introduction

Cryptography is essential in this modern world of computing and communication to protect sensitive information from unauthorized access. It plays a crucial role in ensuring the security and privacy of digital systems including various applications in secure communication, data protection, online transactions and digital signatures. Cryptography is the art of private communication where the information remains exclusive to the sender and the recipient. In this procedure, the initial text referred to as the 'plain text' undergoes transformation into an unintelligible format called the 'cipher text' based on certain algorithms and a key. The process of transforming the original text into a cipher text is termed as 'Encryption' while the reverse operation is called as 'Decryption'. Only the receiver possessing the key or encryp -tion knowledge can decipher the exchanged cipher text. Many traditional and modern encryption algorithms are in existence yet there always remains a necessity to update the system of ciphers to prevent any potential misuse of the established ciphers.

The computational techniques of mathematics paves a way to embed itself in the field of cryptography. Eminent mathematicians and graph theorists have put forward a number of effective encryption mechanisms in [1, 10–12]. The amalgamation of Graph Theory and Linear Algebra has the potential to become a vital instrument in encryption systems. In Graph Theory, the concept of graph coloring has demonstrated its applicability across a wide range of domains [5]. Dominator coloring has been studied for its potential impact in certain fields of optimization. Similarly, there has been a growing research focus on the concept of Latin square and its applications in recent times. In this article, the idea of Latin square graphs in combination with dominator coloring [2] has taken into consideration for an effective encryption procedure.

2 Preliminaries

A brief overview of essential definitions and preliminaries is provided in this section.

Definition 2.1. *[8] A Graph $\mathcal{G} = \{V, E, I\}$ is an ordered triple where V denotes the set of nodes called vertices, E represents the set of links called edges and I is the incidence of a vertex and an edge.*

Definition 2.2. *[7] A subset S of the vertex set V is referred to as a dominating set of a graph $\mathcal{G}$ if every vertex in $V \backslash S$ is adjacent to atleast a vertex in S. The domination number $\gamma(\mathcal{G})$ is the minimum cardinality of a dominating set in $\mathcal{G}$.*

Definition 2.3. *[4] Proper assignment of colors to each vertex in a graph to ensure that no two neighbouring vertices share the same color is termed as proper graph coloring and the least number of colors utilized is the chromatic number.*

Definition 2.4. *[6] Dominator coloring of a graph $\mathcal{G}$ is one of the proper colorings such that each vertex is said to be in the neighbourhood of all the vertices of atleast one color class. The minimum number of colors required for a dominator coloring is known as the dominator chromatic number denoted by $\chi_d(\mathcal{G})$.*

Definition 2.5. *[9] A Latin square can be described as an $n \times n$ array with each symbol from the set $\{0, 1, 2, \ldots, n-1\}$ appearing precisely once in both a row and a column.*

Definition 2.6. *[3] The Latin square graph of a Latin square $\mathcal{L}$ is the simple graph $\Gamma(\mathcal{L})$ whose vertices are the cells of $\mathcal{L}$, and where two cells (r, c, s) and (r', c', s') are adjacent if (exactly) one of the equations $r = r', c = c', s = s'$ is satisfied. Accordingly, each edge of $\Gamma(\mathcal{L})$ is called, respectively, a row edge, a column edge or a symbol edge.*

3 Dominator coloring of the Latin square graphs of the group $(\mathbb{Z}_n, +)$

The group of integers modulo 'n' under addition $(\mathbb{Z}_n, +)$ is an abelian group of order n. The Cayley table of this group is thus a commutative Latin square of order n consisting of the symbols from $\{0, 1, 2, \ldots, n-1\}$ as depicted below in Fig. 1. In this section, the dominator coloring is applied for the Latin square graphs for the group of integers modulo n under addition and the respective dominator chromatic number is found for $n = 2, 3, 4$.

Lemma 3.1. *The dominator chromatic number of the Latin square graphs of the group $(\mathbb{Z}_n, +)$ is*

$$\chi_d(\Gamma(\mathcal{L}(\mathbb{Z}_n, +))) \geq n.$$

Proof.
The proof of this lemma is trivial, since every Latin square graph of order $n \times n$ contains a maximal complete subgraph of order n. □

$+Z_2$	0	1
0	0	1
1	1	0

$+Z_3$	0	1	2
0	0	1	2
1	1	2	0
2	2	0	1

$+Z_4$	0	1	2	3
0	0	1	2	3
1	1	2	3	0
2	2	3	0	1
3	3	0	1	2

Figure 1: Cayley tables of $(+\mathbb{Z}_2, +\mathbb{Z}_3, +\mathbb{Z}_4)$.

Theorem 3.1. *The dominator chromatic number of the Latin square graphs of the group* $(\mathbb{Z}_n, +)$ *is*

$$\chi_d(\Gamma(\mathcal{L}(\mathbb{Z}_n, +))) = \begin{cases} 4, & when\ n = 2 \\ 3, & when\ n = 3 \\ 6, & when\ n = 4 \end{cases} .$$

Proof. By the definition 2.4, the Latin squares are formed according to the Cayley tables of the groups $(+\mathbb{Z}_2, +\mathbb{Z}_3, +\mathbb{Z}_4)$ given in Fig. 1. Since there are $n \times n$ entries, the graph produced contains n^2 vertices. For our reference, the vertices are named with the alphabets $\{a, b, c, \ldots\}$ in equivalence with the elements $\{0, 1, 2, \ldots\}$. They are denoted as $(respective\_alphabet)^{ij}$ where i and j represent the corresponding row and column respectively. The vertices are connected row-wise, column-wise and symbol-wise and thus there are $3n$ number of $K_n' s$ present as maximal complete subgraphs. All the Latin square graphs associated with this group are $3(n-1)$ regular. So the domination number of these graphs, $\gamma(\Gamma(\mathcal{L})) = n - 1$.

Case 1: *n=2*

The Cayley table for the group $(\mathbb{Z}_2, +)$ and the associated Latin square graph is provided in Fig. 2 below:

The graph is obtained as a complete graph of order 4 and the proof is obvious.

$+\mathbb{Z}_2$	**0**	**1**
0	0	1
1	1	0

→

$+$	**a**	**b**
a	a	b
b	b	a

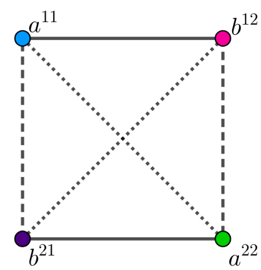

Figure 2: Cayley table and Latin square graph of $+\mathbb{Z}_2$.

Case 2: *n=3*

The Cayley table for the group $(\mathbb{Z}_3, +)$ and the associated Latin square graph is represented in Fig. 3.

$+\mathbb{Z}_3$	**0**	**1**	**2**
0	0	1	2
1	1	2	0
2	2	0	1

→

$+$	**a**	**b**	**c**
a	a	b	c
b	b	c	a
c	c	a	b

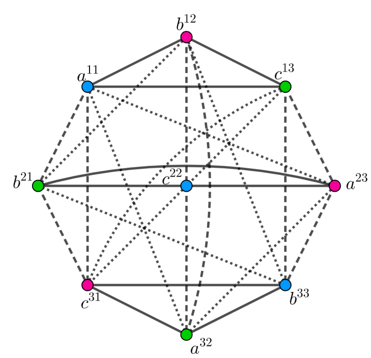

Figure 3: Cayley table and Latin square graph of $+\mathbb{Z}_3$.

In this graph, there are 3 cliques (K_3) formed in each row-adjacency, column-adjacency and symbol-adjacency.

- Initiate the coloring process by assigning numerical values 1, 2, and 3 to the vertices in the first row in sequential order.
- Utilize the same colors to assign the vertices of the last row ensuring the proper coloring algorithm remains undisturbed.
- Given the graph's small size, it allows for the repeated use of the same three colors for the vertices in the middle row.

The completeness of the graph enables each vertex to dominate the other two color classes, resulting in the establishment of a dominator coloring.

Case 3: *n=4*
The Cayley table for the group $(\mathbb{Z}_4, +)$ and the associated Latin square graph is depicted in Fig. 4 below:

$+\mathbb{Z}_4$	**0**	**1**	**2**	**3**
0	0	1	2	3
1	1	2	3	0
2	2	3	0	1
3	3	0	1	2

→

+	**a**	**b**	**c**	**d**
a	a	b	c	d
b	b	c	d	a
c	c	d	a	b
d	d	a	b	c

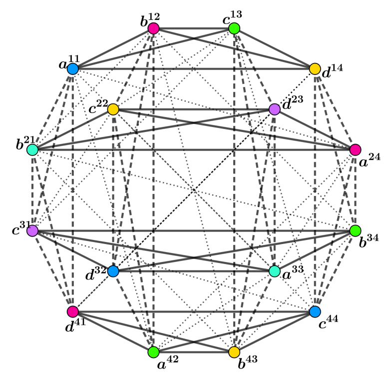

Figure 4: Cayley table and Latin square graph of $+\mathbb{Z}_4$.

The proof is similar to the previous case. In this graph there are 4 cliques (K_4) each in row-adjacency, column-adjacency and symbol-adjacency.

- Start the assignment of colors in numerical order $1, 2, 3, 4$ to the vertices in first row.
- Assign the last row with the coloring sequence $2, 3, 4, 1$ while preserving the proper coloring scheme.
- Since the order of the graph is 4×4, there remains the option to reuse these colors if needed.
- Color the columns 2 and 4 with the used colors cautiously maintaining the proper coloring algorithm.
- The remaining four vertices could only be colored with two new colors 5 and 6 as follows:

  - The vertices b^{21} and a^{33} are colored diagonally with the color 5.
  - The vertices d^{23} and c^{31} are colored diagonally with the color 6.

- This assignment preserves the dominating property as well.

□

4 Application in Cryptography

The concept of dominator coloring of Latin square graphs presents an interesting application in the field of cryptography. In this article, the coloring approach has been applied only for $n = 2, 3, 4$. However, it can be readily extended to any value of n, thereby broadening the potential applications of this idea. The suggested application employs the positions of alphabets rather than the alphabets themselves. Both the encryption and decryption algorithms are put forward using these index positions. Fig. 5 displays the index positions of the alphabets.

A	B	C	D	E	F	G	H	I	J	K	L	M
1	2	3	4	5	6	7	8	9	10	11	12	13

N	O	P	Q	R	S	T	U	V	W	X	Y	Z
14	15	16	17	18	19	20	21	22	23	24	25	26

Figure 5: Index positions of the alphabets

4.1 Encryption Algorithm

1. Start the encryption process by substituting each letter in the word with its respective alphabetic index.
2. In cases where a letter is repeated more than once, replace each subsequent repetition of the index with *(original index of the letter + 26i)*, where i refers to the respective count of repeated letter index. Otherwise, proceed to the step 3.

3. Let 'n' represent the number of letters received in the word. Create the Cayley table for the addition group of integers modulo 'n'.
4. If $l_1, l_2, \ldots, l_n$ represent the letter indices, then assign each index to the elements of the group, i.e., $\{l_1, l_2, \ldots, l_n\} \to \{0, 1, 2, \ldots, n-1\}$
5. Form a matrix O of order $n \times n$, which functions as a Latin square where the letter indices serve as the symbols in accordance with the Cayley table.
6. Write a matrix $M_1 = O + nJ_n$, where J_n denotes the matrix of order n with all entries equal to 1.
7. Interchange the first row of the matrix with the $(n-1)^{th}$ row since the domination number of an $n \times n$ Latin square is always $(n-1)$ in the case of the integers modulo group considered. Let this matrix be M_2.
8. Draw the Latin square graph $\Gamma(M_2)$ for the matrix M_2 and color the vertices using dominator coloring as mentioned in the previous section.
9. Now, create another matrix 'D' that represents the coloring sequence of the rows and columns used in the previous step.
10. Compute $M_3 = M_2 D$.
11. Find the maximum number of color classes dominated by each vertex and denote it as $d(a_{ij})$, where a_{ij} represents the vertex in the i^{th} row and j^{th} column of the Latin square graph $\Gamma(M_2)$.
12. Construct an upper triangular matrix with all its non-zero entities being $max\{d(a_{ij})\}$ and denote this as the Key matrix K.
13. The final cipher text matrix C is obtained using $C = KM_3$.
14. Send the cipher matrix C, the key K and the matrix D.

Fig. 6 provides an overview of the mentioned encryption process.

4.2 Decryption algorithm

1. Receive the cipher matrix C, the key K and the matrix D.
2. Restore the matrix M_3 using the cipher matrix and the key as $M_3 = K^{-1}C$.
3. Reconstruct the matrix M_2 by muliplying the matrices M_3 and inverse of D.

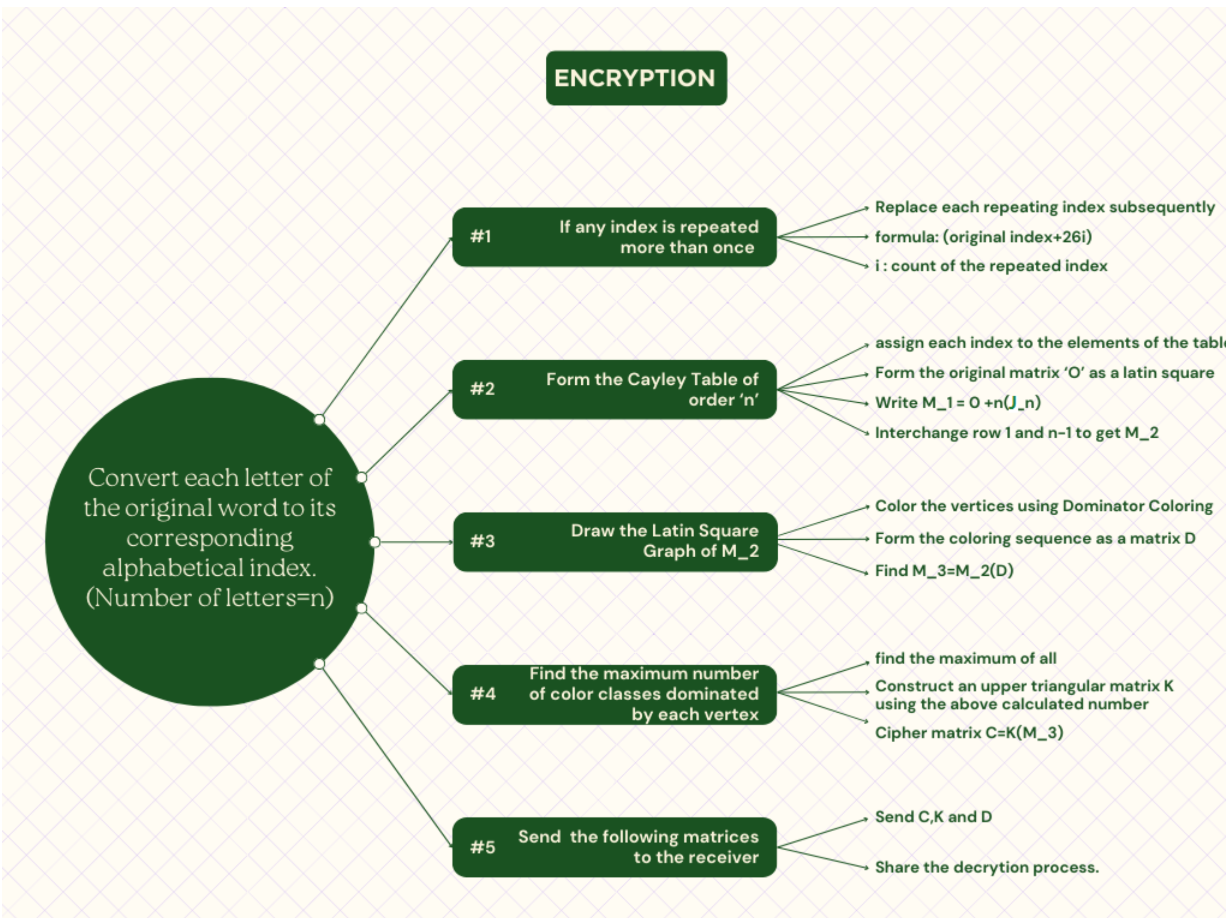

Figure 6: Encryption procedure

4. Discover M_1 by interchanging the first row and $(n-1)^{th}$ row of M_2.

5. Decipher the original matrix from $O = M_1 - nJ_n$.

6. If the first row of the matrix O contains indices greater than 26, then rewrite them using the formula $(current\ index\ value - 26i)$ where

$$i = min\{m\},\ \ if(26{+}m) \leq current\,index\,value \leq 26(m{+}1), m = 1, 2, 3, \ldots$$

7. The first row in the final matrix O corresponds to the sequence of the letter indices of the original word.

4.3 Example

Suppose the word 'NOON' has to be secretly communicated.

ENCRYPTION:
Step 1: The corresponding alphabetic indices are $N = 14$ and $O = 15$. So the row takes the form,

$$\begin{bmatrix} N & O & O & N \end{bmatrix} = \begin{bmatrix} 14 & 15 & 15 & 14 \end{bmatrix}.$$

Step 2: The letters 'N' and 'O' each appear twice, leading to repeated indices. To address this, we apply the rule outlined in step 2 of encryption, which eliminates repetition. Here the letter O is repeated once at the third column and the letter N is repeated once at the last column. Hence, for 'O', the replacement is $15 + 26(1) = 41$ and for 'N', it is $14 + 26(1) = 40$. So the revised assignment will be

$$\begin{bmatrix} 14 & 15 & 15 & 14 \end{bmatrix} = \begin{bmatrix} 14 & 15 & 41 & 40 \end{bmatrix}.$$

Step 3: The number of letters in the given word is 4. So we form the Cayley table for the addition group of integers modulo 4 $(+\mathbb{Z}_4)$.

$+_4$	0	1	2	3
0	0	1	2	3
1	1	2	3	0
2	2	3	0	1
3	3	0	1	2

.

Step 4: We assign each of the letter indices to the elements of the table as

$$\{14, 15, 41, 40\} = \{0, 1, 2, 3\}.$$

Step 5: The matrix O with reference to the table is formed as:

$$O = \begin{bmatrix} 14 & 15 & 41 & 40 \\ 15 & 41 & 40 & 14 \\ 41 & 40 & 14 & 15 \\ 40 & 14 & 15 & 41 \end{bmatrix}.$$

Step 6: Here $n = 4$ and thus J_4 is the matrix with all entries equal to 1.

$$M_1 = O + 4J_4$$

$$M_1 = \begin{bmatrix} 14 & 15 & 41 & 40 \\ 15 & 41 & 40 & 14 \\ 41 & 40 & 14 & 15 \\ 40 & 14 & 15 & 41 \end{bmatrix} + 4 \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} 18 & 19 & 45 & 44 \\ 19 & 45 & 44 & 18 \\ 45 & 44 & 18 & 19 \\ 44 & 18 & 19 & 45 \end{bmatrix}.$$

Step 7: $M_2 = row\ 1 \leftrightarrow row\ 3\ in\ M_1$.

$$M_2 = \begin{bmatrix} 45 & 44 & 18 & 19 \\ 19 & 45 & 44 & 18 \\ 18 & 19 & 45 & 44 \\ 44 & 18 & 19 & 45 \end{bmatrix}.$$

Step 8: The Latin square graph for the matrix M_2 and its dominator coloring is demonstrated in Fig. 7.

Step 9: The sequence from the above coloring assignment can be transformed into another matrix D as provided below.

$$D = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 6 & 4 & 5 & 2 \\ 5 & 1 & 6 & 3 \\ 2 & 3 & 4 & 1 \end{bmatrix}.$$

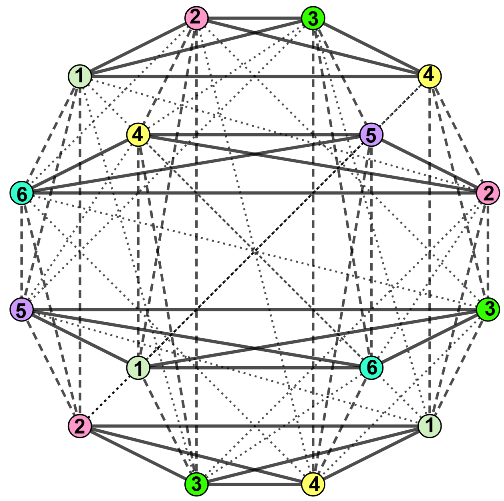

Figure 7: Dominator coloring of $\Gamma(\mathcal{L}(\mathbb{Z}4,+))$

Step 10: The matrix M_3 is computed using $M_3 = M_2D$.

$$M_3 = \begin{bmatrix} 45 & 44 & 18 & 19 \\ 19 & 45 & 44 & 18 \\ 18 & 19 & 45 & 44 \\ 44 & 18 & 19 & 45 \end{bmatrix} \times \begin{bmatrix} 1 & 2 & 3 & 4 \\ 6 & 4 & 5 & 2 \\ 5 & 1 & 6 & 3 \\ 2 & 3 & 4 & 1 \end{bmatrix}$$

$$M_3 = \begin{bmatrix} 437 & 341 & 539 & 341 \\ 545 & 316 & 618 & 316 \\ 445 & 289 & 595 & 289 \\ 337 & 314 & 516 & 314 \end{bmatrix}.$$

Step 11: The number of color classes dominated by each vertex of the above illustrated coloring is given by:

$$d(a_{11}) = 2, d(a_{12}) = 2, d(a_{13}) = 2, d(a_{14}) = 2,$$

$$d(a_{21}) = 1, d(a_{22}) = 2, d(a_{23}) = 2, d(a_{24}) = 2,$$

$$d(a_{31}) = 2, d(a_{32}) = 1, d(a_{33}) = 2, d(a_{34}) = 1,$$

$$d(a_{41}) = 2, d(a_{42}) = 1, d(a_{43}) = 2, d(a_{44}) = 1,$$

Step 12: Here $max\{d(a_{ij})\} = 2$ and hence the key matrix K can be constructed as an upper triangular matrix as follows:

$$K = \begin{bmatrix} 2 & 2 & 2 & 2 \\ 0 & 2 & 2 & 2 \\ 0 & 0 & 2 & 2 \\ 0 & 0 & 0 & 2 \end{bmatrix}.$$

Step 13: The cipher matrix is calculated using $C = KM_3$.

$$C = \begin{bmatrix} 2 & 2 & 2 & 2 \\ 0 & 2 & 2 & 2 \\ 0 & 0 & 2 & 2 \\ 0 & 0 & 0 & 2 \end{bmatrix} \times \begin{bmatrix} 437 & 341 & 539 & 341 \\ 545 & 316 & 618 & 316 \\ 445 & 289 & 595 & 289 \\ 337 & 314 & 516 & 314 \end{bmatrix}$$

$$C = \begin{bmatrix} 3528 & 2520 & 4536 & 2520 \\ 2654 & 1838 & 3458 & 1838 \\ 1564 & 1206 & 2222 & 1206 \\ 674 & 628 & 1032 & 628 \end{bmatrix}.$$

Step 14: The word has been encrypted and the matrices C, K and D is to be sent to the receiver.

DECRYPTION:

Step 1: The cipher matrix C, the key K and the matrix D is received.
Step 2: The matrix M_3 is restored using $M_3 = K^{-1}C$.

$$M_3 = \begin{bmatrix} 1/2 & -1/2 & 0 & 0 \\ 0 & 1/2 & -1/2 & 0 \\ 0 & 0 & 1/2 & -1/2 \\ 0 & 0 & 0 & 1/2 \end{bmatrix} \times \begin{bmatrix} 3528 & 2520 & 4536 & 2520 \\ 2654 & 1838 & 3458 & 1838 \\ 1564 & 1206 & 2222 & 1206 \\ 674 & 628 & 1032 & 628 \end{bmatrix}$$

$$M_3 = \begin{bmatrix} 437 & 341 & 539 & 341 \\ 545 & 316 & 618 & 316 \\ 445 & 289 & 595 & 289 \\ 337 & 314 & 516 & 314 \end{bmatrix}.$$

Step 3: The matrix M_2 is calculated using $M_2 = M_3 D^{-1}$.

$$M_2 = \begin{bmatrix} 437 & 341 & 539 & 341 \\ 545 & 316 & 618 & 316 \\ 445 & 289 & 595 & 289 \\ 337 & 314 & 516 & 314 \end{bmatrix} \times \begin{bmatrix} -1/14 & 11/42 & 1/42 & -13/42 \\ 5/56 & 29/168 & -47/168 & 23/168 \\ -3/28 & -23/84 & 17/84 & 31/84 \\ 17/56 & 3/56 & -1/56 & -15/16 \end{bmatrix}$$

$$M_2 = \begin{bmatrix} 45 & 44 & 18 & 19 \\ 19 & 45 & 44 & 18 \\ 18 & 19 & 45 & 44 \\ 44 & 18 & 19 & 45 \end{bmatrix}.$$

Step 4: Interchange the first and third row of M_2 to get M_1.

$$M_1 = \begin{bmatrix} 18 & 19 & 45 & 44 \\ 19 & 45 & 44 & 18 \\ 45 & 44 & 18 & 19 \\ 44 & 18 & 19 & 45 \end{bmatrix}.$$

Step 5: The original matrix O is found by $O = M_1 - nJ_n$.

$$O = \begin{bmatrix} 14 & 15 & 41 & 40 \\ 15 & 41 & 40 & 14 \\ 41 & 40 & 14 & 15 \\ 40 & 14 & 15 & 41 \end{bmatrix}.$$

Step 6: Here the first row contains two indices 41 and 40 which are greater than 26. By the formula $(current\ index - 26i)$ given in the algorithm, the equivalent values are obtained as

$$41 - 26(1) = 15 \ since \ (26+1) \le 41 \le 26(1+1)$$

$$40 - 26(1) = 14 \ since \ (26+1) \le 40 \le 26(1+1).$$

Step 7: So the first row of the deciphered original matrix is

$$\begin{bmatrix}14 & 15 & 15 & 14\end{bmatrix}.$$

From the alphabetical index table, 14 and 15 corresponds to the letters 'N' and 'O' respectively. Therefore, the plain text is discovered as 'NOON'.

5 Conclusion

The proposed mechanism exhibits quite a strengthened level of encryption thereby preventing any unauthorized access or data theft. The matrix operations performed during encryption could be executed in a fraction of seconds using MATLAB or Python. The dominator coloring technique, when applied to any values of 'n' within the specified group, proves reliable for accommodating various numbers of alphabets, rendering this method highly adaptable. Additionally similar kind of approaches based on the Latin squares and dominator coloring could be performed for the existing cipher methods with some necessary adjustments. While this combination may not be a direct tool for encryption or decryption, it can play an interesting role in improving the security of cryptographic systems or in certain cryptographic protocols. In summary, the integration of Latin squares and dominator coloring with a minimal programming effort, could do wonders in the encryption procedures utilizing a lesser amount of time yet delivering a high level of security.

Conflicts of Interest: The authors declare no conflicts of interest.

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