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Construction and Optimization of TRNG Based Substitution Boxes for Block Encryption Algorithms

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Abstract: Internet of Things is an ecosystem of interconnected devices that are accessible through the internet. The recent research focuses on adding more smartness and intelligence to these edge devices. This makes them susceptible to various kinds of security threats. These edge devices rely on cryptographic techniques to encrypt the pre-processed data collected from the sensors deployed in the field. In this regard, block cipher has been one of the most reliable options through which data security is accomplished. The strength of block encryption algorithms against different attacks is dependent on its nonlinear primitive which is called Substitution Boxes. For the design of S-boxes mainly algebraic and chaos-based techniques are used but researchers also found various weaknesses in these techniques. On the other side, literature endorse the true random numbers for information security due to the reason that, true random numbers are purely non-deterministic. In this paper firstly a natural dynamical phenomenon is utilized for the generation of true random numbers based S-boxes. Secondly, a systematic literature review was conducted to know which metaheuristic optimization technique is highly adopted in the current decade for the optimization of S-boxes. Based on the outcome of Systematic Literature Review (SLR), genetic algorithm is chosen for the optimization of s-boxes. The results of our method validate that the proposed dynamic S-boxes are effective for the block ciphers. Moreover, our results showed that the proposed substitution boxes achieve better cryptographic strength as compared with state-of-the-art techniques.

Keywords: IoT security; sensors data encryption; substitution box generation; True Random Number Generators (TRNG); heuristic optimization; genetic algorithm

1 Introduction

IoT created a new paradime by connecting various devices and everyday objects to the network but now days IoT devices have facing serious security issues to protect the confidentiality of transmitted data. Block ciphers are most reliable option for ensuring the data confidentiality. The strength of block ciphers against different attacks depends on their substitution boxes which provides confusion in the cryptosystem. S-box is a mapping of n-bits inputs to m-bits output and it can be seen as a Boolean function and this can be viewed as $F\colon F_2^n \longrightarrow F_2^m$. In the literature mainly algebraic methods and chaotic maps are used for the construction of S-boxes although there methods have favorable characteristics for S-box designs but many researchers pointed weaknesses in these methods such as Short Quantity of randomness [1–6], Interpolation attacks [7–10], eXtended Sparse Linearization (XSL) attack [11–15], Initial state limitation [16,17], Frail chaos [18,19], Small number of input parameters [20–23], Dynamical degradation [24–27], Gröbner basis attack [27–29], eXtended Linearization(XL) attacks [30–37].

On the other side, randomness is a fundamental aspect of many processes in nature and an indubitably valuable resource for cryptography. Researchers endorse the true random numbers in cryptography due to the fact that true random numbers are irreversible, unpredictable, and unreproducible even if their internal structure and response history is known to the adversaries. We are using the lightning strike phenomenon as an entropy source to generate true random numbers. In this research first of all, we intake the locations of lightning strikes in the row data format from the standard repository of National Aeronautics and Space Administration(NASA) which name is Lightning Detection and Ranging System (LDAR) [38]. Secondly, a novel technique is proposed for the generation of TRNG based substitution boxes. Thirdly genetic algorithm applied for the optimization of newly generated S-boxes but before this phase, a systematic literature review was conducted to know which metaheuristic optimization technique is highly adopted in the last 10 years. Based on the outcome of SLR, a genetic algorithm is chosen. The remaining paper is structured as follows; Sections 2 and 3 present our contribution and the proposed methodology respectively, Section 4 explains the results and evaluation section, Section 5 shows the conclusion section.

2 Contribution

The main contributions of this research are follows:

- A novel method is proposed for the generation of substitution boxes of symmetric encryption algorithms based on true random numbers.
- Multi population genetic algorithm is applied for optimization of substitution boxes.
- A systematic literature review was conducted to know which metaheuristic optimization technique is highly adopted in the last 10 years for the optimization of cryptographic substitution boxes.
- A novel technique proposed for the true random numbers generation.

3 Proposed Design Methodology

The proposed technique has three phase's first phase is true random bits extraction, second phase is construction of substitution boxes and the third phase is optimization of substitution boxes. These three phases are explained in the following and the proposed system architecture is depicted in Fig. 1.

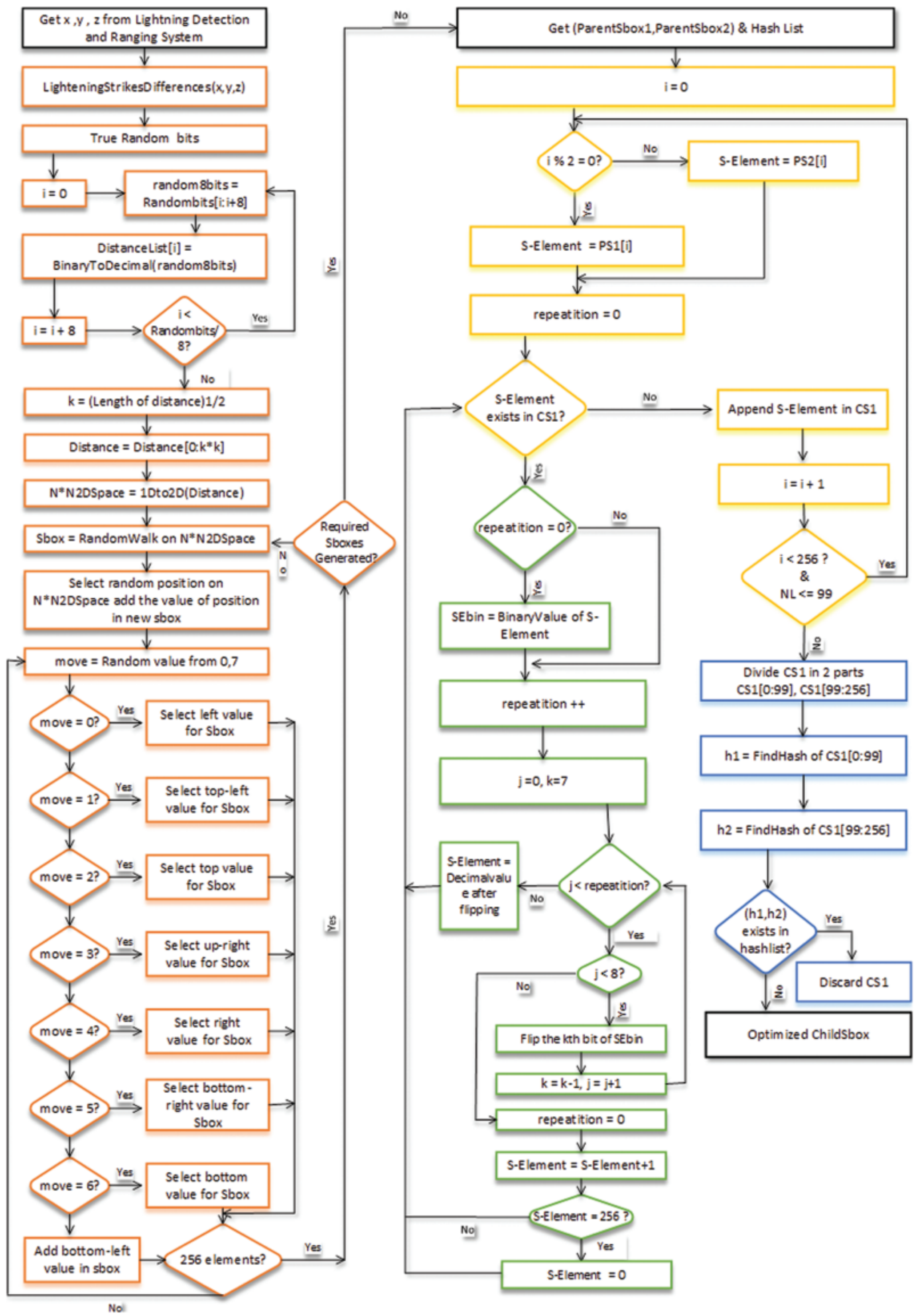


Figure 1: Proposed system architecture

Algorithm 1: SboxConstruction(RandomBits, totalSbox)

```
Input: RandomBits string; integer totalSbox
Output: 1D array of integer values Sbox[ ]
Distance ← list( )
z ← 0
for i ← 0 ... ( | RandomBits | div 8 ) do
        random8bits ← substring( RandomBits,z,z+8 )
        Distance.append( BinaryToDecimal( random8bits) )
        z ← z + 8
end for
k ← ( | Distance | ) ^1/2
Distance ← Distance[ 0 : k ^2 ]
        NxN2DSpace ← 1DTo2DArray( Distance, ( k,k ) )
n ← 0
while ( n != totalSbox) do
        tempSbox ← RandomWalk( NxN2DSpace, k)
        Sbox.append(tempSbox)
        n++
end while
return Sbox
```

3.1 True Random Bits Extraction

To calculate the difference between each location of the lightning strike with other lightning strike locations, firstly we acquire the lightning strike locations (in the row data format) from the standard repository of NASA [38]. Lightning detection and the ranging system is a volumetric lightning mapping system, which stores the real-time location of the striking point. The format of the row data is dd,hh,mm,ss,ll,xx,yy, zz, where dd represents the day of the month, hh represents the hour, mm represents the minute, ss represents second, ll represents microsecond. xx and yy represent the distance in meters from site-1 to the east direction and north direction respectively where zz represents the distance in meters above the surface of the earth. Secondly, each location of the 1st lightning strike is subtracted from the other locations of the lightning strikes. For the experiment, data of the randomly picked 9613227 lightning strikes are processed from the proposed algorithm and then resultant binary stream enhanced through the Von Neumann extractor, after this, these random bits are tested through the National Institute of Standards and Technology (NIST) statistical test suite. Results of the NIST statistical test (shown in Appendix A) proved that lightning strikes are useful entropy source for the generation of true random numbers.

3.2 Construction of Substitution Boxes

In the first step of dynamic substitution boxes construction, an algorithm proposed which name is SboxConstruction(). This algorithm takes, true random bits from the last phase and a total number of required S-boxes from the user as parameters. In the second step SboxConstruction() algorithm, further calls the RandomWalk() algorithm by passing the two-dimensional $N * N$ space of truly random bits. On every run RandomWalk() algorithm generates a single dynamic s-box by using the 8 states random walk rule (left = 0, left up = 1, up word = 2, right up = 3, right = 4, right down = 5, down = 6, left down = 7). SboxConstruction() algorithm is presented in the above. Randomly we plotted the two RandomWalk() runs as sample in the Figs. 2a and 2b and their resultant S-boxes in the Tabs. 1a and 1b. For the results, the total number of ten thousand S-boxes are constructed, where the nonlinearity score of 1674 S-boxes are ≤ 99, nonlinearity score of 3277 S-boxes are between 100 to 102, nonlinearity score of 4126 S-boxes are between 103 to 104, nonlinearity score of 923 S-boxes are between 105 to 106. The nonlinearity score of our sample S-boxes 2a, 2b is 105 and 104 respectively. As sample TRNG based S-box is shown in the Appendix B.

Table 1a: Proposed Sbox-1

155	253	60	189	42	238	93	209	202	129	164	75	240	85	151	254
44	138	251	28	223	230	95	62	231	121	149	31	180	57	161	73
203	72	84	227	218	210	56	243	245	190	135	9	69	255	219	166
140	198	239	225	250	143	120	63	134	103	186	207	2	64	27	144
241	37	108	92	98	65	220	79	4	249	228	24	205	10	102	156
8	122	119	185	188	58	236	216	226	17	217	13	35	237	78	242
80	33	127	125	14	83	192	66	221	169	48	112	59	100	146	74
199	97	141	52	173	107	224	68	55	152	247	110	157	181	170	196
131	32	104	86	96	128	50	208	158	244	214	159	234	142	22	118
81	43	6	89	187	7	177	67	204	171	5	235	195	123	0	139
109	3	178	172	18	54	76	53	99	88	212	46	21	39	15	201
101	87	246	184	165	233	105	179	232	206	49	70	252	126	191	147
114	71	229	26	1	29	132	248	91	154	25	211	16	106	34	111
116	183	168	117	193	51	47	137	115	200	174	153	133	20	213	194
45	40	124	150	130	11	77	175	12	222	19	160	30	182	82	41
61	113	36	167	38	136	145	163	90	94	162	23	215	176	197	148

Table 1b: Proposed Sbox-2

211	238	81	126	89	185	244	26	139	143	23	73	209	102	132	120
34	174	78	159	165	114	138	181	10	28	221	250	44	189	110	191
155	128	223	75	164	72	214	108	25	245	201	213	2	109	178	144
216	96	123	196	197	121	150	86	35	169	27	90	166	163	56	158
117	147	15	6	47	17	100	252	57	79	156	212	198	218	131	162
101	186	30	104	242	202	146	122	133	253	103	130	87	16	192	168
54	205	125	149	33	107	153	32	129	179	12	173	251	157	195	42
224	227	20	207	180	36	145	84	231	200	255	61	97	43	170	91
11	49	210	148	204	24	13	215	52	46	183	193	171	154	222	88
137	94	85	40	167	95	140	45	106	237	99	74	234	175	21	151
4	119	77	184	105	92	83	243	177	226	51	134	39	182	68	236
82	118	248	0	70	247	55	67	37	8	230	136	48	208	188	142
41	232	246	235	71	113	127	69	5	116	22	249	64	80	93	50
53	219	1	161	76	160	172	176	225	63	152	254	187	115	98	239

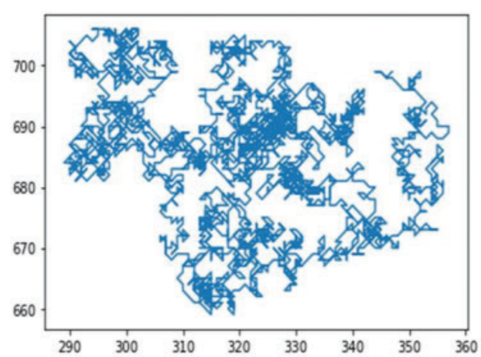
(Continued)

Table 1b: Continued

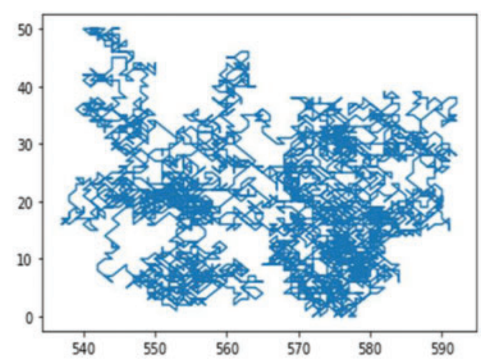
31	29	62	220	18	112	206	194	229	241	240	217	228	111	141	38
135	203	3	233	19	65	14	190	199	58	66	59	60	9	124	7

Table 1c: Optimized Sbox-3

162	5	201	199	126	220	204	9	155	242	2	39	166	221	133	15
63	192	73	164	254	23	11	185	247	34	98	149	40	22	96	33
176	75	113	53	50	165	44	29	132	156	169	206	225	85	0	208
36	103	64	218	198	122	137	136	104	159	118	88	154	32	193	57
183	135	160	24	228	152	234	172	17	177	232	70	175	210	14	31
142	188	227	141	151	76	219	131	119	197	212	251	65	100	97	145
190	68	158	110	214	61	146	116	3	238	101	49	181	54	239	92
179	147	30	143	109	170	223	215	157	51	250	106	153	13	241	79
129	140	78	18	248	6	196	252	58	89	184	134	115	59	203	124
81	112	195	84	74	235	82	28	105	243	237	230	95	173	80	94
138	83	66	12	38	45	87	10	191	121	86	99	189	217	249	168
236	102	231	1	205	107	62	202	233	253	27	56	144	72	8	125
167	55	128	25	255	229	187	178	35	246	171	226	26	240	47	16
211	77	117	41	20	67	123	180	111	91	174	224	7	46	52	127
120	108	182	244	222	207	150	60	130	148	42	139	194	93	21	216
209	161	48	245	4	37	19	43	114	90	69	213	186	71	163	200



(a)



(b)

Figure 2: Plotted S-boxes (a) 8-steps random walk of Sbox-1 (b) 8-steps random walk of Sbox-2

3.3 Optimization of Substitution Box

The most important strength of true random-based construction of S-boxes is that, these S-boxes are immune against the attacks which are mentioned in the introduction section. This is our first goal which is achieved in the above Sections 3.2 by using the true randomness. The 2nd goal of this research is to find out, which metaheuristic optimization technique is effective (highly adopted) in existing literature for the optimization of S-boxes (which are not based on true randomness). To discover the answer to this question, a SLR was conducted over the last 10 years. Query wise search results of SLR is mentioned in the Tab. 2 and based on the SLR recommendation, a technique is presented in the following for the optimization of newly constructed S-boxes using the genetic algorithm. Reverse S-box algorithm for the TRNG and GA based S-boxes is shown in the Appendix C.

Table 2: Query wise search results

Query	IEEE	Springer	ACM	Elsevier
Genetic algorithm and S-boxes	14	241	33	62
Genetic algorithm and substitution box	5	93	24	29
Genetic algorithm and nonlinear block cipher primitive	4	0	66	0
Genetic algorithm and confusion component	5	3	54	0
Simulate annealing and S-boxes	4	99	13	19
Simulate annealing and substitution box	1	39	9	6
Simulate annealing and nonlinear block cipher primitive	0	0	14	0
Simulate annealing and confusion component	0	0	17	0
Tabu search and substitution box	0	4	10	2
Tabu search and S-boxes	2	9	12	8
Tabu search and nonlinear block cipher primitive	0	8	14	0
Tabu search and confusion component	0	0	14	0
Particle swarm optimization and S-boxes	2	79	51	21
Particle swarm optimization and substitution box	1	30	48	8
Particle swarm optimization and nonlinear block cipher primitive	0	0	48	0
Particle swarm optimization and confusion component	5	0	39	0
Artificial bee colony optimization and substitution box	1	9	48	1
Artificial bee colony optimization and S-boxes	2	8	50	3
Artificial bee colony optimization and nonlinear block cipher primitive	0	0	1	0
Artificial bee colony optimization and confusion component	0	0	6	0

GA is based on the Charles Darwin's theory of natural selection and survival of the fittest In the standard genetic algorithm, selection, crossover, and mutation are the common processes. In our problem for the selection process, all the substitution boxes whose nonlinearity score lies in the range of 100 to 106 are acquired as the initial population. For the crossover process, we used the one-point crossover strategy in which pair of parents exchange the half part of each parent to each other and generate new offspring. Complete crossover process is represented with yellow color in the flowchart which is depicted in Fig. 1. Widely in the literature [39–44], the nonlinearity score is the highly desirable property that's why we also chose the nonlinearity score as the fitness value. In the conventional genetic algorithm, crossover and mutation are the two independent processes but here for the substitution box generation, we combine the crossover and mutation process together. The reason is that, the substitution boxes generated by the crossover operation usually do not satisfy the bijective property due to repeated elements. So, repetition must be removed from the new offspring to achieve the bijective property and for that purpose, a simple strategy is adopted in the mutation process. In the mutation process we flipped the one bit from right side to the left side, and after flipping each bit, the corresponding number is checked within the s-box. If the corresponding number is unique, then we stop the flipping process, otherwise we flip the next bit and so on. In the numerous cases, we achieved the bijective property but in the few cases after flipping the eight bits, we did not get the unique element of the s-box and in those cases, we simply add one to the original element from where we start the flipping process. The mutation process is represented with green color in the flowchart of Fig. 1. From the results, we observed that numerous S-boxes and their subsets are repeated therefore we used SHA-3 based searching for removal and this process is shown with blue color in the flowchart. Here, for the experiment hundred thousand S-boxes are optimized and to examine the performance, we compared the highest quality ten thousand optimized S-boxes with the ten thousand S-boxes which are already constructed through the TRNG based technique. After optimization, it can be clearly seen from Fig. 3 that GA improves the overall quality of the S-Boxes. After optimization process, there are no S-box having non-linearity of less than and equal to 99 where TRNG based S-box construction technique 1674 S-boxes in that range. Similarly, GA produce more S-boxes in the range of 105 and 106 as compared to TRNG construction method. Furthermore, GA produce 616 new S-boxes having non-linearity of 107 and 108 and these S-Boxes were not discovered in TRNG based approach.

4 Results and Evaluation

In this section sample S-boxes of Section 3.2 are evaluated through the S-box evaluation criteria which are shown in the following 4.1 to 4.5.

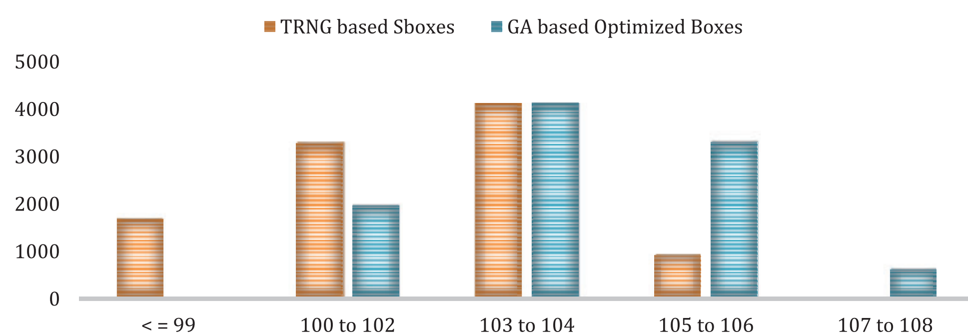


Figure 3: Nonlinearity score of TRNG and GA based S-box construction

4.1 Nonlinearity

Out of all cryptographic properties, nonlinearity is said to be the most significant. For a strong encryption scheme, the mapping between input and output in an S-box must be nonlinear.

Nonlinearity can be defined as the smallest distance of Boolean function to the set of affine functions. To get the closet affine function in the Boolean truth table, the total number of bits altered needs to be determined by the nonlinearity score. In the above Fig. 3 we saw that six hundred sixteen S-boxes attains a 108 nonlinearity score and from these S-boxes, we picked randomly one S-box as a sample which is shown in Tab. 1c. The Nonlinearity scores of proposed S-boxes are better or equal to the state-of-the-art. S-boxes which are shown in Tab. 3. By using Walsh spectrum, the nonlinearity of Boolean function is determined as:

$$N_g = 2^{n-1}(1 - 2^{-n} \max_{\varphi \epsilon GF(2^n)} |S(g)(\varphi)|) \tag{1}$$

$$\text{where } S_{(g)}(\varphi) \text{is defined as: } S_{(g)}(\varphi) = \sum_{\varphi \in GF(2^n)} (-1)^{g(x) \oplus x.\varphi} \tag{2}$$

where φ is a n-bit vector and $\varphi \in GF(2^n)$. The dot product between x and φ is denoted by $x.\varphi$

$x.\varphi = x1 \oplus \varphi 1 + x2 \oplus \varphi 2 \cdot + xn \oplus \varphi n.$

Table 3: Nonlinearity of various S-boxes

S-box	Nonlinearity	S-box	Nonlinearity
Ozkaynak [45], 2020	104	EI-Latif [46], 2020	107
Zahir et al. [47], 2020	104	EI-Latif [48], 2020	106
Faheem et al. [49], 2020	104	Liu et al. [50], 2017	108
Akram et al. [51], 2017	108	Özkaynak [52], 2018	108
Ünal et al. [53], 2017	106	Solami et al. [54] 2018	108
Lambić et al. [55], 2017	108	Lambić [56], 2020	106

4.2 Strict Avalanche Criteria (SAC)

SAC computes the number of output bits altered caused by inverting a single bit of input. To make the system more reliable, we need to deviate output vector with half probability when one input bit is inverted. To evaluate the SAC property, dependency matrix are used. For an S-box that can satisfy SAC property, all values need to be close to ideal value of 0.5 in its dependence matrix. The SAC value of our randomly picked optimized S-box is 0.501465 which satisfies the avalanche criteria. The offsets of the dependence matrix can be determined by:

$$S(g) = \frac{1}{n^2} \sum_{1 \le r \le n} \sum_{1 \le w \le n} \left| \frac{1}{2} - Qr, w(g) \right| \tag{3}$$

$$\text{where } Qr, w(g) = 2^{-n} \sum_{x \epsilon B^n} gw(x) \oplus gw(x \oplus e_r) \tag{4}$$

$e_r = [\theta r, 1\ \theta r, 2 \ldots ; \theta r, n]^T\ \theta_{r,w} = 0, r \neq w \text{ or } \theta r, w = 1, r = w$

4.3 BIT Independent Criterion (BIC)

BIC is another cryptographic metric used to measure the efficiency of S-boxes. For an S-box to satisfy the BIC property, all avalanche variables should be independent pair wise for a number of avalanche vectors created by modifying a single bit of plaintext. BIC states that reversing the input bit i modifies the output bits j and k in such a way that the no dependency lies between output bits. This would tend to improve the confusion function's effectiveness. To satisfy the BIC property, the output bits must exhibits independent behavior. Therefore, efforts are being made to decrease the dependency of output bits. The correlation coefficient is used to calculate the degree of independence among avalanche variable pairs. The bit independence of the jth and kth bits of Bei is:

$$BIC\left(b_j, b_k\right) = \max_{1 \le i \le n} |corr(b_j^{ei}, b_j^{ei'}| \quad (5)$$

S-box function (h) is defined as: h: {0, 1}n →{0, 1}n .BIC parameter for the S-box function is expressed as follows:

$$BIC\,(h) = \max_{1 \le j,k \le n} BIC(b_j, b_k) \quad (6)$$

Average SAC-BIC score of our optimized S-box is 0.49937. Which is almost optimal and indicates that proposed S-box fulfills the required criteria.

4.4 Linear Approximation Probability (LP)

LP is used to evaluate the security of S-box against linear cryptanalysis. S-box provides diffusion and confusion of bits through linear mapping between input and output. Maximum imbalance of an event is determined by LP. The input bit's parity given by the mask $\gamma 1$ is equal to the output bit's parity given by the mask $\gamma 2$. Linear approximation probability is represented as:

$$\mathrm{LP} = \max_{\gamma 1, \gamma 2 \neq 0} \left| \frac{\{x\epsilon X | x.\gamma 1 = S\,(x)\,.\gamma 2\}}{2^n} - \frac{1}{2} \right| \quad (7)$$

where the input mask is represented by $\gamma 1$, $\gamma 2$ represents the output mask. These masks are used to calculate the linear approximation probability. X denotes the set of all possible inputs and 2n is the total number of elements in the S-Box. An S-box having low linear probability represents high nonlinear mapping and have high resistance against linear cryptanalysis. The maximum optimized S-box LP value is 0.140625 which fulfills the desired criterion.

4.5 Differential Approximation Probability (DP)

Differential approximation probability means that output shall have a difference of Δy every time the input is changed by Δx. DP examines the XOR distribution between input and output bit. Variations in output can be obtained from variations in input. For resilience against differential attacks, XOR values of all outputs and inputs must have equal probability. The exclusive-OR distributions among the inputs and outputs of S-box is calculated by:

$$\mathrm{DP}\,(\Delta x \longrightarrow \Delta y) = \left[\frac{\#\{x\epsilon X | (S(x) \oplus S\,(x \oplus \Delta x) = \Delta y\}}{2^n} \right] \quad (8)$$

where X represents the set of all possible input values, 2n is a total number of all the elements in the S-box, Δx and Δy are the input and output differentials. S-boxes with small differentials values are strong and good at resisting differential cryptanalysis. The DP results of Sbox1 are following in the Tab. 4, and we can see that our proposed S-box fulfils the DP criteria.

Table 4: DP of the S-box1

.000000	.023438	.023438	.023438	.031250	.023438	.023438	.023438	.031250	.023438	.023438	.023438	.023438	.023438	.031250	.023438
.023438	.023438	.023438	.023438	.023438	.031250	.023438	.031250	.023438	.031250	.023438	.023438	.023438	.023438	.031250	.023438
.023438	.015625	.031250	.023438	.023438	.039062	.031250	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438
.023438	.023438	.031250	.031250	.023438	.031250	.023438	.031250	.031250	.031250	.031250	.023438	.031250	.023438	.031250	.046875
.039062	.023438	.031250	.023438	.023438	.039062	.023438	.023438	.031250	.031250	.023438	.023438	.023438	.023438	.023438	.031250
.023438	.031250	.023438	.023438	.023438	.023438	.031250	.031250	.023438	.023438	.023438	.031250	.031250	.031250	.023438	.023438
.023438	.031250	.023438	.023438	.023438	.023438	.023438	.031250	.039062	.023438	.039062	.023438	.031250	.031250	.031250	.023438
.039062	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.023438	.031250	.023438
.023438	.023438	.039062	.031250	.023438	.023438	.023438	.023438	.023438	.039062	.023438	.023438	.039062	.031250	.023438	.023438
.023438	.023438	.031250	.031250	.023438	.023438	.023438	.023438	.023438	.023438	.031250	.031250	.023438	.023438	.023438	.031250
.023438	.023438	.031250	.023438	.023438	.023438	.031250	.023438	.023438	.023438	.031250	.039062	.023438	.031250	.031250	.023438
.023438	.023438	.023438	.023438	.023438	.031250	.023438	.023438	.023438	.031250	.023438	.023438	.023438	.023438	.031250	.023438
.031250	.039062	.031250	.023438	.023438	.039062	.031250	.023438	.039062	.031250	.023438	.023438	.031250	.031250	.023438	.031250
.031250	.023438	.023438	.023438	.023438	.031250	.023438	.023438	.023438	.023438	.023438	.031250	.023438	.023438	.023438	.023438
.023438	.031250	.031250	.023438	.023438	.031250	.023438	.023438	.023438	.031250	.031250	.023438	.023438	.031250	.031250	.023438
.023438	.023438	.031250	.023438	.031250	.015625	.039062	.023438	.023438	.031250	.023438	.023438	.039062	.031250	.023438	.023438

4.6 Substitution Permutation based Image Encryption

In this section simple Substitution Permutation Network (SPN) used for the image encryption. Detailed steps of the SPN are mentioned bellow. Here for the substitution step optimize S-boxes of the Section 3.3 used, we used the P-boxes and keys from the [57].

Step-1: Extract the Red, Green and Blue channel values from the color image frames and repeat the following steps-2 to step-4 for every channel(R or G or B).

Step-2: Perform the bitwise XOR between the plain pixel values and sub key_i to obtain the key additive pixel values.

Step-3: Replace each value of step-2 with entries of the optimized ($Sbox_i$) values.

Step 4: Diffuse the each value of step-3 by using ($P\text{-}box_i$) values.

Step 5: Repeat step-2 to step-4 for $i<16$.

Step 6: Combine the individual R, G, B encrypted pixel values into a single frame.

The NPCR and UACI are the two frequently used tests of the image cipher to check the strength against various attacks. NPCR, UACI are used to evaluate a large number of plain images to measure the impact of pixel change on the encrypted images. We examined the image encryption results on various standard color images (Lena, pepper, nature, bird, baboon, grapes, sparrow, butterfly). Ideal image encryption algorithm must produce different results when a pixel of the image is slightly varied. NCPR is the rate of change in the number of pixels between two encrypted images obtained from two slightly different images. To achieve maximum sensitivity in an algorithm the value of NCPR should close to 100%. UAIC measure the mean variation of pixel intensity of two encrypted images at same location. Following Tab. 5 indicates the values of NPCR and UACI. Constantly our NPCR values are around to 99.63 which is the very good value. Similarly the UACI values are around 33.5 which is also the good value.

Table 5: NPCR and UACI results

Images	Location	NPCR Proposed	UACI Proposed	Images	Location	NPCR Proposed	UACI Proposed
Lena	R	99.6221	33.5514	Baboon	R	99.6578	33.6534
	G	99.6127	33.5158		G	99.6256	33.6385
	B	99.5517	33.5212		B	99.6344	33.7265
Pepper	R	99.6231	33.4525	Grapes	R	99.6231	33.7596
	G	99.6462	33.4642		G	99.6652	32.7821
	B	99.6652	33.4935		B	99.6632	33.5063
Nature	R	99.5925	33.6789	Sparrow	R	99.6551	33.4798
	G	99.6186	33.4987		G	99.6225	33.4125
	B	99.6245	33.6506		B	99.6432	32.9098
Bird	R	99.6621	33.4065	Butterfly	R	99.6591	33.5215
	G	99.6651	32.9154		G	99.6652	32.9952
	B	99.6266	32.9365		B	99.6063	33.0563

5 Conclusion

The IoT-based computationally intelligent schemes are expanding due to the growing concerns of privacy leakage and security attacks in connected systems. It has added a new potential to the internet by enabling communications between objects and humans, making a smarter and more intelligent ecosystem. In this regard, block encryption algorithms have been a standout amongst the most reliable option by which data security is accomplished. The strength of block encryption algorithms against different attacks is dependent on its nonlinear primitive which is called S-boxes. The objective of this research is dynamic generation and optimization of highly secure S-boxes for the block encryption algorithms. For this purpose we used the true random numbers as the entropy source of the proposed method because true random numbers are irreversible, unpredictable, and unreproducible. The proposed method passes all the security evaluation criteria including nonlinearity, linear approximation probability, differential approximation probability, strict avalanche criterion, bit independence criterion, differential analysis, histogram analysis, correlation coefficient tests, NPCR, and UACI tests. The results of our method validate that the proposed dynamic s-boxes are effective for the block encryption algorithms. In the future, we will extend this research to the design of cryptographic key generation technique for the IoT systems.

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Appendix A:

Type of Test	P-Value		Conclusion
01. Frequency Test (Monobit)	6.711666215580028e−17		Non-Random
02. Frequency Test within a Block	0.21575971288691256		Random
03. Run Test	0.0		Non-Random
04. Longest Run of Ones in a Block	0.16958128602983685		Random
05. Binary Matrix Rank Test	0.7750321912480472		Random
06. Discrete Fourier Transform (Spectral) Test	0.44626281343698193		Random
07. Non-Overlapping Template Matching Test	0.014635340688886967		Random
08. Overlapping Template Matching Test	0.36023946288540937		Random
09. Maurer's Universal Statistical test	0.7544062853856957		Random
10. Linear Complexity Test	0.9996378217856143		Random
11. Serial test:			
	0.5165245696277773		Random
	0.6762539065001036		Random
12. Approximate Entropy Test	0.06688206161079184		Random
13. Cummulative Sums (Forward) Test	3.1895223249735723e−17		Non-Random
14. Cummulative Sums (Reverse) Test	3.13591282948427e−17		Non-Random
15. Random Excursions Test:			
State	Chi Squared	P-Value	Conclusion
−4	1.411911703456893	0.923005839169952	Random
−3	2.4854000000000003	0.7786922371169736	Random
−2	5.354938271604938	0.37411466651616343	Random
−1	5.25	0.3861379243372883	Random
+1	2.5	0.7764950711233227	Random
+2	2.567901234567901	0.7662360828950802	Random
+3	2.7176	0.7434253074909452	Random
+4	3.424406497292795	0.6348554712380596	Random
16. Random Excursions Variant Test:			

(Continued)

Appendix A: Continued

Type of Test		P-Value		Conclusion
	State	COUNTS	P-Value	Conclusion
	−9.0	25	0.6995916043003889	Random
	−8.0	36	0.3613104285261789	Random
	−7.0	40	0.23931654122149537	Random
	−6.0	42	0.16580656019401352	Random
	−5.0	30	0.40939548620991884	Random
	−4.0	20	0.7892680261342813	Random
	−3.0	16	1.0	Random
	−2.0	18	0.8382564863858263	Random
	−1.0	16	1.0	Random
	+1.0	18	0.7236736098317631	Random
	+2.0	16	1.0	Random
	+3.0	12	0.7518296340458492	Random
	+4.0	8	0.5929800980174267	Random
	+5.0	5	0.5168677495508638	Random
	+6.0	2	0.45554509378932995	Random
	+7.0	2	0.49245682377288025	Random
	+8.0	1	0.4935627897033894	Random

Appendix B:

147	81	50	43	92	245	182	30	237	34	42	39	53	246	219	188
1	221	161	76	158	213	160	197	185	164	184	251	223	99	47	27
172	107	146	83	176	180	171	183	109	56	225	80	64	155	173	63
15	105	235	163	230	234	193	82	89	177	117	152	216	110	137	91
162	133	174	122	102	129	108	169	72	116	113	254	22	121	68	204
249	187	12	115	69	54	95	5	126	94	17	24	77	250	86	154
222	98	11	165	101	33	87	85	226	25	179	168	201	224	239	70
31	138	149	96	208	181	106	209	100	215	88	8	139	210	29	104
40	62	36	52	44	49	220	21	227	218	74	231	18	112	212	150
206	192	189	211	153	127	10	194	229	6	103	45	134	241	240	217
214	178	75	142	120	16	252	144	228	55	136	242	118	2	195	71
202	186	13	28	243	166	148	84	111	141	67	170	167	132	51	123
93	37	38	248	145	79	135	175	32	78	156	238	203	236	61	232
23	130	143	3	90	35	233	46	196	151	48	159	19	20	119	65
73	14	131	200	97	190	128	157	244	205	26	207	125	199	41	140
58	57	4	66	253	59	247	60	114	9	198	255	124	191	7	0

Appendix C:

Algorithm: ReverseSbox (S-box)

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in: 2D array of integers, sbox [16] [16];
out: 2D array of integers, ReverseSbox [16] [16];
ReverseSbox → |16||16|
for row → 0 ... (16) **do**
    for col → 0 ... (16) **do**
        rowIS → sbox $_{\text{row,col}}$ **div** 16
        colIS → sbox $_{\text{row,col}}$ **mod** 16
        value → row∗16+col
            ReverseSbox $_{\text{rowIS,colIS}}$ → value
    end for
end for
return ReverseSbox
