Providing End-to-End Security Using Quantum Walks in IoT Networks

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ABSTRACT Internet of Things acts an essential role in our everyday lives and it definitely has the potential to grow on the importance and revolutionize our future. However, the present communication technologies have several security related issues which is required to provide secure end to end connectivity among services. Moreover, due to recent, rapid growth of quantum technologies, most common security mechanisms considered secure today may be soon imperilled. Thus, the modern security mechanisms during their construction also require the power of quantum technologies to resist various potential attacks from quantum computers. Because of its characteristics, quantum walks (QW) is considered as a universal quantum computation paradigm that can be accepted as an excellent key generator. In this regard, in this paper a new lightweight image encryption scheme based on QW for secure data transfer in the internet of things platforms and wireless networking with edge computing is proposed. The introduced approach utilises the power of nonlinear dynamic behaviour of QW to construct permutation boxes and generates pseudo-random numbers for encrypting the plain image after dividing it into blocks. The results of the conducted simulation and numerical analyses confirm that the presented encryption algorithm is effective. The encrypted images have randomness properties, no useful data about the ciphered image can be obtained via analysing the correlation of adjacent pixels. Moreover, the entropy value is close to 8, the number of the pixel change rate is greater than 99.61%, and there is high sensitivity of the key parameters with large key space to resist various attacks.

INDEX TERMS Quantum walks, lightweight cipher, data transfer in IoT, image encryption, edge computing, wireless communication.

I. INTRODUCTION

The Internet of Things (IoT) has heightened an integral part of the future of communication systems [1], [2]. It promises vast interconnections of ''things'' including everything, every-one, everywhere, every time and every network. Within this concept, smart nodes comprising devices, sensors, services, applications, etc. will be able to seamlessly inter-act and communicate in real time. In addition, to inter-connecting devices, IoT will usher in web-enabled exchange of data which will enhance service delivery. Moreover, IoT will also provide a platform to integrate the physi-cal world with the virtual one. From this perspective, con-sidering the envisioned importance of IoT, data security should be treated as the backbone of data transfer in IoT environments.

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The protection of data transfer from unauthorized access in IoT systems becomes a pressing issue and is increasingly investigated by experts and researchers [3]–[8]. Techniques for protecting digital information can be roughly classified into two groups. The first type is data encryption and the other is data hiding [9]–[14]. In this context, data encryption refers to transformations of the original data from an intelligible form into an unidentifiable one [15]. Digital images are one of the common data representation patterns which are extensively used in numerous applications.

Recently, various image encryption mechanisms have been proposed [16]–[22] and most of them are based on mathematical models such as chaotic systems. Nevertheless, because of the periodicity chaos property, most chaotic models are unstable [23]. Consequently, most chaos-based image encryption mechanisms are susceptible to attacks [24].

Quantum computers have shown promise for operations unrivalled by the best-known digital resources due to quantum phenomena like quantum superposition and quantum entanglement [25], [26]. Considering its roots in quantum mechanics, which relies on the linear algebraic formulations as well as applications in computing, device fabrication, etc., quantum computing is a promising concept for a wide range of disciplines including physics, mathematics, computer science, and engineering. This multidisciplinary undertaking is already shaping innovations and technologies in information theory, communication, cryptography, image processing and electronics, among many other fields. In all these areas, quantum computation has been deployed to improve the existing non-quantum algorithms and technologies. Moreover, the reinvigorated efforts to realize physically scalable quantum hardware have reinforced the belief that when (not if) quantum computers are fully completed they will be capable of solving many computing issues considered intractable via available (digital) resources.

However, in the wrong hands, the immense capabilities of quantum computing can be misused. In this manner, they pose unprecedented threat to today's information security mechanisms. These threats range from exploiting the vulnerabilities inherent to cybersecurity frameworks to issues or gaps arising from the transition or widespread prevalence of quantum computing hardware. Therefore, modern cryptographic mechanisms require incorporating quantum technology to withstand possible attacks from quantum devices in the near future [27]. In this regard, risks related to data transfer in IoT platforms would be greatly mitigated or eliminated via advanced cryptographic mechanisms based on quantum technologies.

Quantum walks (QW) is considered as a universal quantum computational model [28]–[30], that can be accepted as a good key generator because of its inherent nonlinear chaotic dynamical behaviour [31]–[40]. QW similarly to chaos has chaotic behaviour and high sensitivity to initial conditions. Moreover, QW possesses advantages like non-periodicity, stability and theoretically infinite keyspace to withstand various attacks. In this manner, El-Latif et al [32] presented a novel idea for cascading quantum inspired QWs with chaotic systems and present its cryptographic application. Also, Yang et al [33] designed an image encryption mechanism using two-walker QW. Then, Yang et al [34] presented a new scheme for constructing hash function using controlled two-walker QW and introduced its application to image encryption, Next, El-Latif et al [35] constructed a substitution-box mechanism based on two-walker QW and presented its application in image steganography. However, the implementation of two-walker QW requires more physical resources than the realization of one-walker QW [41], that is why consequently Abd-El-Atty et al [36] designed a quantum encryption approach based on controlled one-walker QW. Finally, El-Latif et al [37] presented an image encryption approach using controlled alternate QW for privacy preserving medical images in IoT systems.

The key contribution of this paper is a proposal of a new lightweight image cipher scheme using one-walker QWs on a circle for secure data transfers in IoT platforms. The aspects of the new scheme is based on lightweight structure in confusion and diffusion processes. It utilises the power of nonlinear dynamics of QW to construct P-boxes for confusion and to generate PRNGs in diffusion. At first, the original object is divided into blocks, and then each block is divided into two subblocks: right subblock and left subblock. Each subblock before recombination with each other is permuted and substituted with its own P-box and PRNG sequence that originates from the probability distribution of running QW. The ciphered blocks are combined together and then XORed with another PRNG sequence to construct the ciphered image. Several enclosed simulation and numerical analyses are conducted based on differential and statistical analyses, which affirm the effectiveness of the proposed cipher. The resulted cipherimages have randomness properties, no useful data about the ciphered image can be obtained via analysing the correlation of adjacent pixels. Moreover, the entropy value is close to the optimal value, NPCR test rate is greater than 99.61%, and there is high key sensitivity in the parameters of the keys with large key space to resist various cyberanalysis.

The key contributions of our paper can be summarized as:

- Propose a new lightweight cipher scheme using QWs.
- The presented mechanism is utilised for securing data transfers in IoT platforms.
- The aspects of the presented cryptosystem are based on a lightweight structure in confusion and diffusion processes.
- The presented mechanism utilises the power of nonlinear dynamics of QW to construct P-boxes for confusion and to generate PRNGs for diffusion stage.

The outline of this work is as follows: the preliminary knowledge for QW is presented in Section II, while the proposed framework for secure data transfers in IoT environments is presented in Section III. Next, Section IV presents our lightweight image encryption approach, while the numerical analyses and simulation outcomes are given in Section V. Finally, Section VI concludes our work.

II. PRELIMINARY KNOWLEDGE

There are two models of quantum walks: continuous-time quantum walk and discrete-time quantum walk (QW) [28]. In this paper, we focus only on QW, which is widely used in designing modern cryptographic applications [31]–[40]. The elementary components of running one-walker QW acting on a circle have two quantum systems: a particle $|\psi\rangle_p$ known as a walker living in a p-dimensional Hilbert space H_p and a 2-dimensional quantum system $|\psi\rangle_c = \cos\ \alpha|0\rangle + \sin\ \alpha|1\rangle$ known as a coin living in Hilbert space H_c. The total Hilbert space of the QW is $H = H_p \otimes H_c$. In every step r of running QW on a circle, the unitary transformation $\hat{R}$ is executed on the whole quantum system $|Q\rangle$. The unitary transformation $\hat{R}$ can be expressed as in Eq. (1).

$$\hat{R} = \hat{F}(\hat{I} \otimes \hat{U}) \tag{1}$$

here $\hat{F}$ points to the shift operator and can be stated for running QW on a circle with T vertices as in (2).

$$\hat{F} = \sum_{i=0}^{T-1} (|(i+1)\ \mathrm{mod}\ T, 0\rangle\langle i, 0| + |(i-1)\ \mathrm{mod}\ T, 0\rangle\langle i, 1|) \tag{2}$$

Also, operator $\hat{U}$ points to a coin operator 2×2 and in general case can be stated as in (3)

$$\hat{U} = \begin{pmatrix} \cos\ \beta & \sin\ \beta \\ \sin\ \beta & -\cos\ \beta \end{pmatrix} \tag{3}$$

After r steps, the final state $|Q\rangle_r$ can be stated as in (4)

$$|Q\rangle_r = \left(\hat{R}\right)^r |Q\rangle_0 \tag{4}$$

and after r steps, the probability of locating the particle at location i can be expressed as in (5)

$$P(i, r) = \left| \langle i, 0| \left(\hat{R}\right)^r |Q\rangle_0 \right|^2 + \left| \langle i, 1| \left(\hat{R}\right)^r |Q\rangle_0 \right|^2 \tag{5}$$

III. PROPOSED FRAMEWORK FOR SECURE DATA TRANSFERS IN IoT PLATFORMS

IoT covers a huge amount of information, which refers to a rapidly growing network of objects or connected devices that are able to collect data using sensors and share this data via networks, e.g. Internet [42]. The immense potential of IoT has seen its use in many areas, including smart cities, smart homes, smart cars, telemedicine, etc. [2], [43]. These vastly interconnected devices need to gather real-time information and connect them to other cloud resources to collect, store, and analyse different data streams [44]. All these processes have an impact on privacy and security of sensitive information. For example, the confidential health records of patients, geotagging people's location using wearable devices [45], [46] need to be safely guarded against the ever-increasing sophistication of criminals. In smart cities, IoT can include important data to control and monitor installations as well as private information of inhabitants of the city [43], [47]. Securing such sensitive information from malicious attacks becomes currently the most pressing aspect

of IoT [48]. Currently, the security fabric of the Internet is not sufficient due to the lack of appropriate security and integrity, susceptibility to systems and physical access, etc. Apart from these issues, since most devices communicate in a wireless manner thus IoT applications should work perfectly in the presence of security challenges. To deal with these security risks a system that is capable to identify and diagnose attacks in necessary. Due to the low-capacity of IoT devices, operations need to be performed using lightweight security mechanisms that can deal with various attacks [49]. With subsisting centralized security solutions which require heavyweight computing and large memory, finding solutions for lightweight security for IoT scenarios is a challenge with many open research areas. That is why, in this paper we provide a new lightweight cipher using one-walker QW for secure data transfers in IoT systems. The presented framework is based on QW to deal with various attacks and resist the feasible threats from quantum computers in the coming future. The outline of the presented framework is provided in Fig. 1.
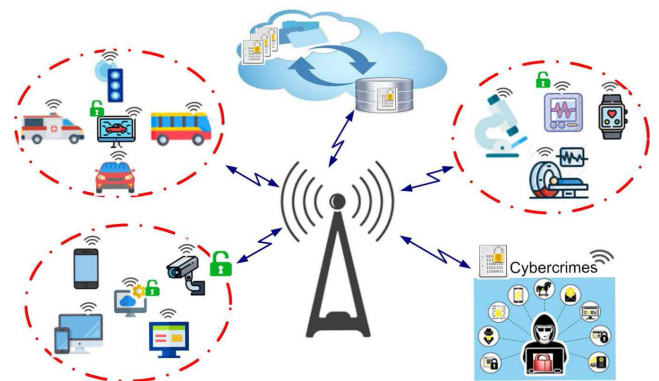

FIGURE 1. Propounded framework for secure data transfers in IoT.

IV. PROPOSED LIGHTWEIGHT IMAGE ENCRYPTION MECHANISM

In this section, we introduce a new lightweight image encryption mechanism using one-walker QW. The presented solution utilises the capabilities of nonlinear dynamics of QWs to generate PRNG sequences and construct P-boxes. At first, the original image is divided into blocks each of size 16×16, and then each block is divided into two subblocks: right subblock (RB) and left subblock (LB). Each subblock before recombination is permuted and substituted with its own P-box and PRNG that originates from the probability distribution of acting one-walker QW on a circle. The ciphered blocks are combined together and then XORed with another PRNG sequence to construct the cipher image. The suggested lightweight image encryption algorithm is outlined in Fig. 2 and the encryption and decryption procedures are presented in Algorithms 1 and 2, respectively.

V. SIMULATION RESULTS

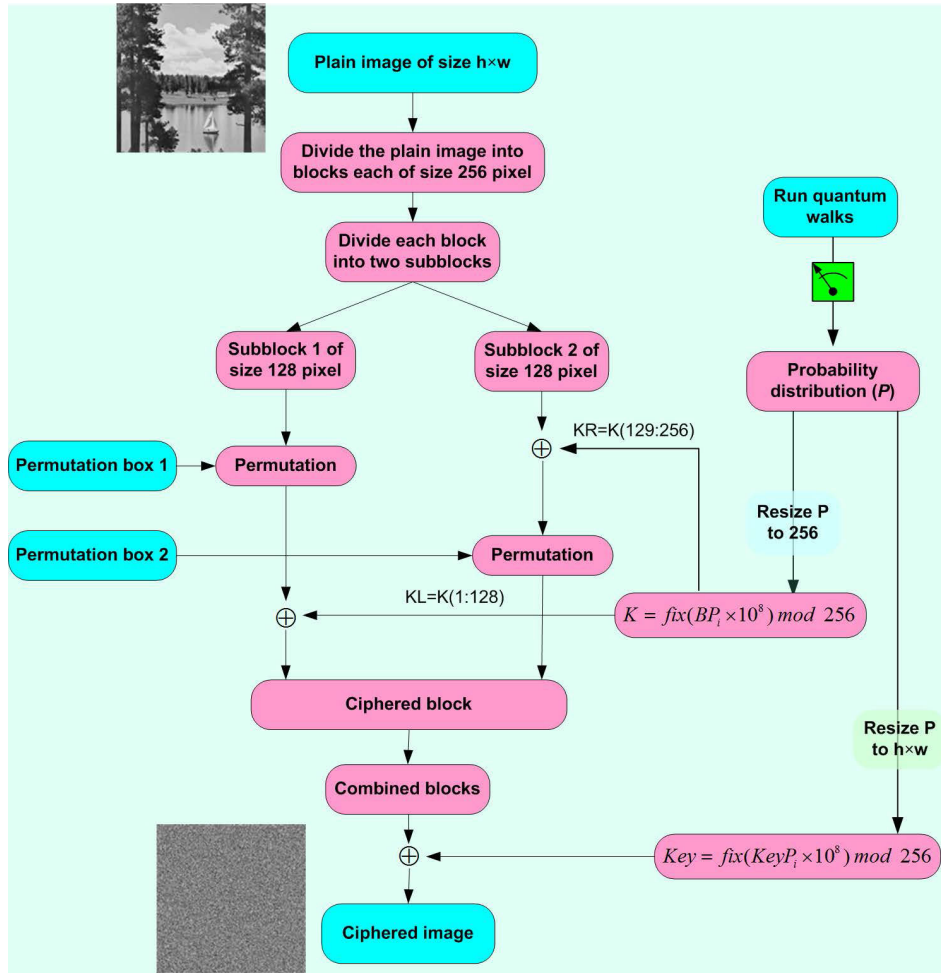To validate the presented image encryption mechanism, we utilised a laptop with 6-GB RAM and Intel *Core*^{TM}

FIGURE 2. The encryption procedure where the permutation and substitution procedures are based only on QWs and the procedure of constructing permutation boxes is provided in Fig. 3.
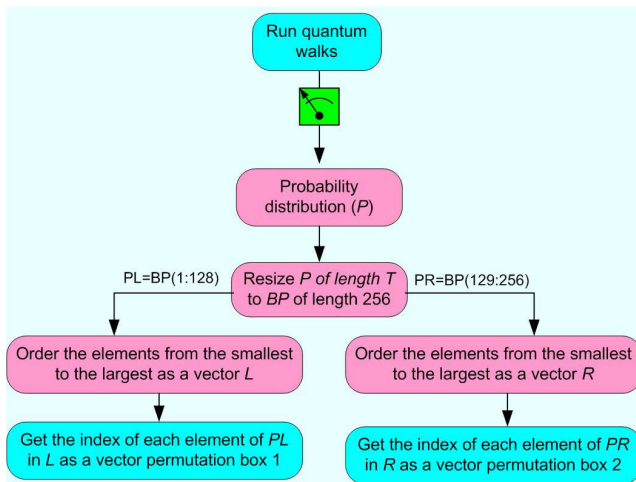

FIGURE 3. The procedure of constructing permutation boxes which are used to permutate subblocks.

i5 CPU 2.50-GHz with preinstalled MATLAB R2016b. The used dataset of images (Sailboat, Baboon, Houses, and Aerial) consists of greyscale images each of size 512×512

(see Fig. 4), while the initial values utilized for operating one-walker QW on a circle are ($T = 241$, $r = 265$, $\alpha = 0$, $\beta = \pi/3$).

A. RANDOMNESS ANALYSIS

NIST SP 800-22 tests are applied to investigate the randomness behavior of the produced key (key sequence) and the constructed cipher image (CIm) and they consist of 15 tests that are applied on a 10^6 bit sequence. The NIST results of key sequence (Key) and the cipher Sailboat image (Enc-Sailboat) are stated in Table 1, which passed all randomness tests. Therefore, the proposed encryption mechanism can be reliably used on modern cryptographic mechanisms.

B. CORRELATION ANALYSIS

One of the most important tools to evaluate an ciphered image is its correlation coefficient of adjacent pixels Cor_{pc}. The typical images have Cor_{pc} close to 1 in each direction while in ciphered images with a well-designed encryption mechanism it should be near 0. To measure Cor_{pc} of the plain and ciphered images, we picked at random 10^4 pairs

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Algorithm 1 Encryption Procedure

Input: Plain image (PIm) and key parameters for running one-walker QW(T, r, α, β)
Output: Cipher-image (CIm)

1 $P \leftarrow QW(T,\ r,\ \alpha,\ \beta)$ // Run quantum walks on a circle of odd T vertices for r steps, where the initial walker is $H_c = \cos\ \alpha|0\rangle + \sin\ \alpha|1\rangle$, and β is used to construct the operator $\hat{U}$ where $\alpha, \beta \in [0, \pi/2]$

2 $[h\ w] \leftarrow size(PIm)$ // Gets the size of the plain image
   // Construct two permutation boxes each of length 128 (see Fig.3)

3 $BP \leftarrow Resize(P, [1\ 256])$ // Resize the probability distribution P of length T to BP of length 256
   // For constructing permutation box1

4 $PL \leftarrow BP(1:128)$

5 $L \leftarrow order(PL)$ // Arrange in ascending order the elements of sequence PL

6 $P - box1 \leftarrow index(PLinL)$ // For each element in sequence PL, gets its index in sequence L
   // For constructing permutation box2

7 $PR \leftarrow BP(129:256)$

8 $R \leftarrow order(PR)$

9 $P - box2 \leftarrow index(PRinR)$

10 $K \leftarrow fix(BP \times 10^8)\ \mathrm{mod}\ 256$ // Converting BP sequence into integer values

11 $KeyP \leftarrow Resize(P, [1\ h \times w])$ // Resize P of length T to h×w

12 $Key \leftarrow fix(KeyP \times 10^8)\ \mathrm{mod}\ 256$

13 $Key \leftarrow reshape(Key, h, w)$ // Transform the key sequence into matrix

14 $Blocks[\ ] \leftarrow dividePImintoblockseachofsize16 \times 16$

15 **for** *each Block* $\leftarrow Blocks[\ ]$ **do**

16    $block \leftarrow reshape(block, 1, 256)$

17    $LB \leftarrow block(1:128)$ // Subblock1

18    $RB \leftarrow block(129:256)$ // Subblock2

19    $RB1 \leftarrow bitxor(RB, K(129:256))$ // Substitute subblock2

20   **for** $i \leftarrow 1$ *to* 128 **do**

21       $LB1(i) \leftarrow LB(P - box1(i))$ // Permute subblock1

22   **for** $i \leftarrow 1$ *to* 128 **do**

23       $RB2(i) \leftarrow RB1(P - box2(i))$ // Permute subblock2

24    $LB2 \leftarrow bitxor(LB1, K(1:128))$ // Substitute subblock1
   // Combine the cipher subblock1 and subblock2

25    $Encblock(1:128) \leftarrow LB2$

26    $Encblock(129:256) \leftarrow RB2$

27    $Encblock \leftarrow reshape(Encblock, 16, 16)$

28    $EncIm \leftarrow combineEncblockintoEncImimage$

29 $CIm \leftarrow bitxor(EncIm, Key)$ // cipher image

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of adjoining pixels. The Cor_{pc} can be calculated via Eq. (6)

$$Cor_{pc} = \frac{\sum_{i=1}^{N}(p_i - \bar{p})(c_i - \bar{c})}{\sqrt{\sum_{i=1}^{N}(p_i - \bar{p})^2 \sum_{i=1}^{N}(c_i - \bar{c})^2}} \qquad (6)$$

here N indicates the entire number of adjacent pixel pairs in each direction and c_i, p_i are pointing to the values of adjacent pixels. Table 2 displays the outcomes of Cor_{pc} for ciphered images and as it can be seen they are very close to 0 as well as the original ones. Also, Fig. 5 displays the correlation distribution in each direction for Sailboat image as well as for its ciphered version. From the outcomes stated in Table 2 and

the acquaintance displayed in Fig. 5, no useful data can be inferred about the ciphered image by analysing Cor_{pc} values.

C. NPCR

NPCR ("Number of pixel change rate") is a tool utilized to calculate the influence of varying pixel values in the plain image on the identical ciphered ones, which can be expressed as in (7).

$$NPCR = \frac{\sum_{a;b} D(a, b)}{A} \times 100\%,$$

$$D(a, b) = \begin{cases} 0\ if\ P(a, b) = C(a, b) \\ 1\ if\ P(a, b) \neq C(a, b) \end{cases} \qquad (7)$$

Algorithm 2 Decryption Procedure

Input: Cipher-image (CIm) and key parameters for running one-walker QW(T, r, α, β)
Output: Decrypted-image (DIm)

1 $P \leftarrow QW(T, r, \alpha, \beta)$ `// Run quantum walks on a circle of odd T vertices for r steps`
2 $[h\ w] \leftarrow size(CIm)$ `// Gets the size of the ciphered image`
   `// Construct two permutation boxes each of length 128 (see Fig. 3)`
3 $BP \leftarrow Resize(P, [1\ 256])$ `// Resize the probability distribution P of length T to BP of` length 256
   `// For constructing permutation box1`
4 $PL \leftarrow BP(1:128)$
5 $L \leftarrow order(PL)$
6 $P - box1 \leftarrow index(PLinL)$
   `// For constructing permutation box2`
7 $PR \leftarrow BP(129:256)$
8 $R \leftarrow order(PR)$
9 $P - box2 \leftarrow index(PRinR)$
10 $K \leftarrow fix(BP \times 10^8 \mod 256$ `// Converting BP sequence into integer values`
11 $KeyP \leftarrow Resize(P, [1\ h \times w])$
12 $Key \leftarrow fix(KeyP \times 10^8) \mod 256$
13 $Key \leftarrow reshape(Key, h, w)$ `// Transform the key sequence into matrix`
14 $DecIm \leftarrow bitxor(CIm, Key)$ `// bitwise XOR operation`
15 $Blocks[\ ] \leftarrow divideDecImintoblockseachofsize16 \times 16$
16 **for** *each Block* $\leftarrow Blocks[\ ]$ **do**
17     $block \leftarrow reshape(block, 1, 256)$
18     $LB \leftarrow block(1:128)$ `// Subblock1`
19     $RB \leftarrow block(129:256)$ `// Subblock2`
20   **for** $i \leftarrow 1 to 128$ **do**
21        $RB1(P - box2(i)) \leftarrow RB(i)$ `// Permute subblock2`
22     $LB1 \leftarrow bitxor(LB, K(1:128))$ `// Substitute subblock1`
23     $RB2 \leftarrow bitxor(RB1, K(129:256))$ `// Substitute subblock2`
24   **for** $i \leftarrow 1 to 128$ **do**
25        $LB2(P - box1(i)) \leftarrow LB1(i)$ `// Permute subblock1`
      `// Combine the decrypted subblock1 and subblock2`
26     $Decblock(1:128) \leftarrow LB2$
27     $Decblock(129:256) \leftarrow RB2$
28     $Decblock \leftarrow reshape(Decblock, 16, 16)$
29     $DIm \leftarrow combineDecblockintoDImimage$

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here A indicates the whole number of pixels in the image, C and P point to the ciphered and plain images, respectively. The NPCR outcomes for the examined dataset are provided in Table 3, in which we can see that NPCR values are greater than 99.612%. As a result, it can be concluded that the suggested approach is highly sensitive to tiny pixel mutations in the original image.

D. HISTOGRAM ANALYSIS

Histogram analysis represents the frequency of pixel distribution in an image. A robust encryption approach ought to guarantee the uniform distribution for distinct ciphered images to stand toward statistical attacks. The histograms of the images from the utilized dataset are illustrated in Fig. 6. Note that they are dissimilar from each other. At the same time, the histograms of their corresponding encrypted versions are practically identical. This means that the presented algorithm could resist histogram analyses attack.

E. GLOBAL ENTROPY ANALYSIS

One of the most important statistical tests to indicate the pixel values distribution for each level in the image is global entropy which can be expressed as follows:

$$E(X) = -\sum_{i=0}^{255} p(x_i) \log_2 (p(x_i)) \qquad (8)$$

here $p(x_i)$ refers to the probability of x_i. There are 2^8 possible values for a greyscale image, therefore, in an ideal case entropy should be equal to 8 bits. Hence, to assert the
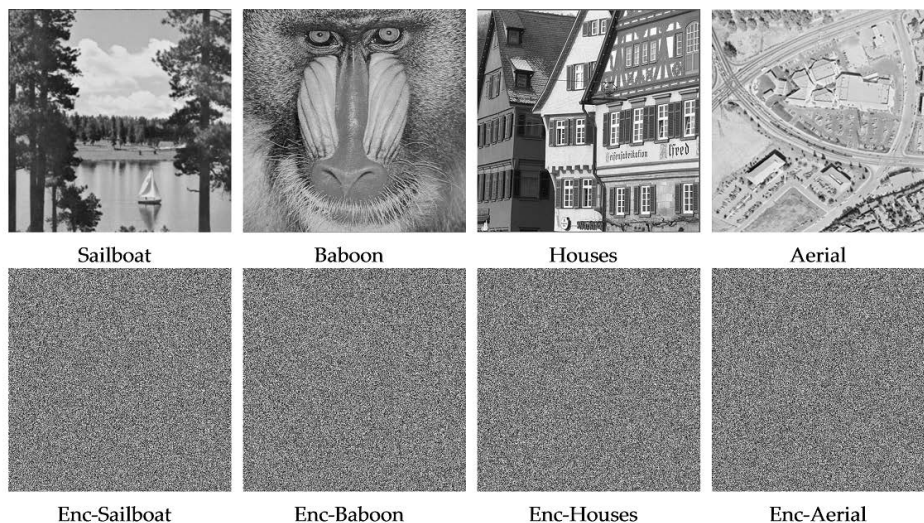
FIGURE 4. The first row of images represents the experimental dataset of images each of size 512 × 512, while the second row represents its corresponding ciphered versions.
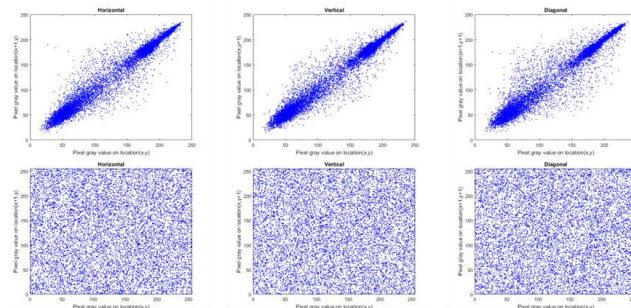
TABLE 1. Outcomes of NIST SP 800-22 tests.

Name of the test	P-Value		Passed
	Key	Encrypted Sailboat	
Long runs of ones	0.645169	0.822031	Yes
Runs	0.469972	0.675904	Yes
Rank	0.865578	0.466365	Yes
DFT	0.890517	0.970719	Yes
Block-frequency	0.297495	0.996969	Yes
Frequency	0.469066	0.807231	Yes
Universal	0.154155	0.745735	Yes
No overlapping templates	0.868040	0.393861	Yes
Overlapping templates	0.988637	0.857940	Yes
Cumulative sums (reverse)	0.764505	0.673618	Yes
Cumulative sums (forward)	0.794907	0.462727	Yes
Linear complexity	0.943555	0.776374	Yes
Approximate entropy	0.802852	0.238003	Yes
Random excursions variant x=1	0.709448	0.406777	Yes
Random excursions x=1	0.515296	0.872236	Yes
Serial test 1	0.355836	0.833744	Yes
Serial test 2	0.157145	0.728918	Yes

TABLE 2. Cor_{pc} values for the utilized experimental dataset.

image	Direction		
	Horizontal	Vertical	Diagonal
Sailboat	0.9726	0.9762	0.9598
Enc-Sailboat	-0.0029	0.0001	-0.0009
Baboon	0.76030	0.8608	0.7230
Enc- Baboon	-0.0016	-0.0012	0.0014
Houses	0.9188	0.9047	0.8292
Enc- Houses	0.0004	0.0015	0.0029
Aerial	0.8693	0.9021	0.8130
Enc-Aerial	0.0016	-0.0006	-0.0011

FIGURE 5. Cor_{pc} of two neighbouring pixels for Sailboat image, where the first row denotes the plain Sailboat image, and the last row indicates its ciphered version.

TABLE 3. NPCR values for the experimental dataset.

Image	NPCR %
Sailboat	99.61204
Baboon	99.62501
Houses	99.61318
Aerial	99.62082

FIGURE 6. Histograms of the encrypted and original images from the dataset.
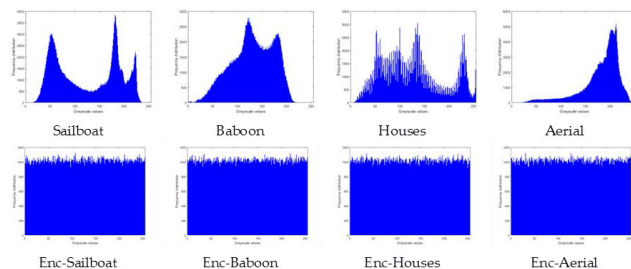
effectiveness of the designed mechanism, the value of entropy for the ciphered image must be as near to 8 as possible. Table 4 shows the outcomes of information entropy for the original images and the corresponding ciphered ones. Note that, all outcomes of information entropy for the ciphered images are extremely close to 8 bits. Thus, the suggested approach is secure under entropy attacks.

TABLE 4. Values of information entropy.

Image	Original	Encrypted
Sailboat	7.45696	7.99926
Baboon	7.35788	7.99930
Houses	7.65475	7.99925
Aerial	6.99399	7.99924

TABLE 5. Comparison of average values of correlation coefficients, information entropy, and NPCR of the proposed approach with other related schemes which its construction is based on QWs.

Algorrithm	Correlation			NPCR %	Entropy
	H	V	D		
Proposed	-0.00063	-0.00005	0.00057	99.618	7.9993
Ref. [32]	0.0002	0.00135	0.0006	99.614	7.9972
Ref. [36]	-0.0067	-0.0021	-0.0027	99.58	7.9971
Ref. [37]	-0.0022	-0.0025	-0.0035	99.619	7.9981
Ref. [40]	-0.0023	-0.0031	-0.0091	99.598	7.9972

F. KEY SPACE AND KEY SENSITIVITY ANALYSES

A robust encryption approach should have a sufficient keyspace to withstand brute-force attacks. Our encryption mechanism is based on running one-walker QW on a cycle where the initial values (T, r, α, β) are required for operating QW. By considering the calculation precision for digital computers as 10^{-16}, the total keyspace of the encryption algorithm is 2^{212}, which is sufficient for any encryption mechanism. Moreover, the key space can be enriched by running controlled one-walker QW on a circle [36].

Key sensitivity is an essential test to ensure the security of any encryption mechanism, which is known as the sensitivity of the initial key parameters to the deciphered effect. To assess the key sensitivity of the presented mechanism, the ciphered Sailboat image is deciphered with tiny changes of initial values as shown in Fig. 7.
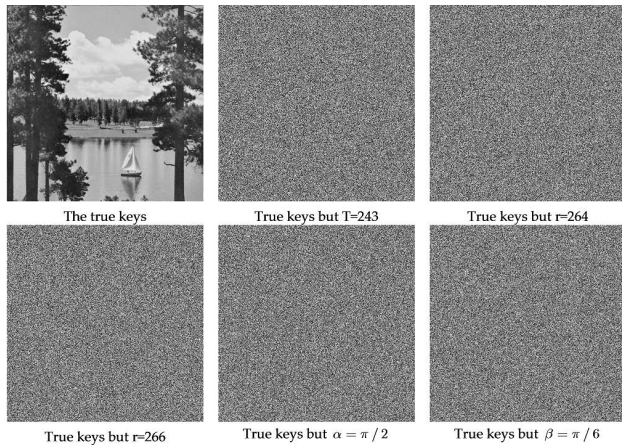

The true keys — True keys but T=243 — True keys but r=264 — True keys but r=266 — True keys but $\alpha = \pi/2$ — True keys but $\beta = \pi/6$

FIGURE 7. Decrypted image Sailboat with several keys.

G. DISCUSSION

We have designed a new lightweight image encryption mechanism based on QWs for securing data transfers in IoT platforms. The presented solution utilises the capabilities of nonlinear dynamics of QWs to generate PRNG sequences and construct P-boxes. At first, the plain image is divided into blocks, and then each block is divided into two subblocks. Each subblock before recombination with each other is permutated and substituted with its own P-box and PRNG sequence that originates from the probability distribution of running QW. The ciphered blocks are combined together and then XORed with another PRNG sequence to construct the ciphered image. Several enclosed simulation and numerical analyses are conducted based on differential and statistical

analyses, which affirm the effectiveness of the proposed cipher. The resulted cipher images have randomness properties, no useful data about the ciphered image can be obtained via analyzing the correlation of adjacent pixels. Moreover, the entropy value is close to the optimal value, NPCR test rate is greater than 99.61%, and there is high key sensitivity in the parameters of the keys with large keyspace to resist various cyberanalysis. In addition, to ensure the effectiveness of the presented mechanism, Table 5 provides a comparison with other related schemes which its construction is based on QWs.

VI. CONCLUSIONS

This work has introduced a new lightweight image encryption mechanism which is based on QW and which is destined for secure data transfers in IoT environments. The proposed solution utilises the probability distribution of running one-walker QW to construct P-boxes and to generate PRNG sequences for encrypting a plain image after dividing it into blocks. Perfomed simulations and statistical analysis confirmed that the suggested encryption scheme has high efficiency in terms of randomness tests, correlation coefficients, NPCR, information entropy, and histogram analysis. In addition to the formulation and application presented here, our proposal can be applied in digital computers as quantum-inspired quantum-walk protocols. Along the same lines, our approach can be utilized as quantum-inspired quantum-walk procedures for designing various encryption applications such as video, file, audio, etc.

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