

When an attacker meets a cipher-image in 2018: A Year in Review

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Abstract

This paper aims to review the encountered technical contradictions when an attacker meets the cipher-images encrypted by the image encryption schemes (algorithms) proposed in 2018 from the viewpoint of an image cryptanalyst. The most representative works among them are selected and classified according to their essential structures. Almost all image cryptanalysis works published in 2018 are surveyed due to their small number. The challenging problems on design and analysis of image encryption schemes are summarized to receive the attentions of both designers and attackers (cryptanalysts) of image encryption schemes, which may promote solving scenario-oriented image security problems with new technologies.

Keywords: image encryption, cryptanalysis, plaintext attack, image privacy, multimedia content protection.

1. Introduction

Security and privacy protection of image data is an everlasting challenge in the cyberspace. Designing image encryption schemes (algorithms, techniques, methods) and further processing in the domain of the cipher-images received intensive attention from researchers in the field of security, signal processing, nonlinear science, and etc [1]. From Web of Science Core Collection, we found about 1,000 publication records published in the year 2018 by inputting “image” and “cryptograph* or encrypt*” in the field of “Topic”. Some more were published in some top conferences on nonlinear sciences and signal processing, e.g. ISCAS and ICME.

In cryptography, substitution-permutation network is the structure of some modern block ciphers such as AES (Advanced Encryption Standard), where an S-box (substitution-box) is used to substitute input of the S-box by another block of bits. Following the framework of Fridrich’s image encryption scheme cryptanalyzed in [2], many image encryption schemes adopting permutation-then-diffusion without substitution-box (PTDWOS) have been proposed since 1998 [3, 4, 5]. Only a few chaotic image encryption schemes use S-box such as [6, 7, 8]. There are some papers focusing on designing S-box with chaotic maps [9, 10, 11, 12]. In [6, 13, 14, 15, 16, 17, 18, 19, 20], the analyzed image encryption schemes were fixed to withstand the proposed attacking methods. Due to the seem-

ingly similar properties of a chaotic system and a secure pseudo-random number generator (PRNG), a large number of image encryption schemes use various chaotic maps to generate PRNS (pseudo-random number sequence), which is used to control combination of some basic encryption operations, e.g. Logistic map [21, 22], Tent map [12, 23], Cat map [24], PWLCM (piecewise linear chaotic map) [25, 26], and coupled map lattice [27]. Rigorously, only the encryption schemes using special chaos methodologies can be classified as chaos-based encryption schemes, e.g. chaos synchronization [28, 29]. As the opposite of image cryptography, some impressive image cryptanalysis works were developed in 2018 [30, 31, 32, 33, 34, 35]. Especially, all image encryption schemes published in the journal *Nonlinear Dynamics* before 2018 are critically reviewed in [35].

This paper selected and classified the representative methods of protecting and disclosing image data proposed in 2018. Some challenges existing in the two sides were concluded from the perspective of a senior cryptanalyst. For example, only a few image encryption schemes focus on real specific application, e.g. wireless communication [36], surveillance [37]. This paper aims to let designers and cryptanalysts of image encryption (and privacy protection) schemes glimpse the annual progress on confrontation between attackers and protectors of image data.

The remainder of the paper is organized as follows. Section 2 reviews the design of image encryption schemes proposed in 2018. Then, Sec. 3 presents a survey on cryptanalytic works on image security given in the last year. Section 4 summarizes the challenges on the two sides on image

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security. The last section concludes the paper.

2. Survey on image cryptography

2.1. Image encryption schemes based on chaos

According to essential structure and the used methodologies, the encryption schemes using chaotic system are coarsely classified in the following five sub-sections.

2.1.1. Randomness-oriented chaos enhancement

To counteract dynamics degradation of chaotic maps in digital computer and enhance randomness of PRNS generated by iterating a chaotic system, various strategies were proposed, e.g. cascading two existing chaotic maps [38]; iteratively expanding a parametric 2-D Cat matrix to any higher dimension [24]; arbitrarily combining six basic non-linear operations [39]; anti-control [40]; constructing hyperchaotic system [41]. In [38], Hua et al. design a sine-transform-based chaotic system (STBCS) of generating one-dimensional (1-D) chaotic maps by performing a sine transform to the combination of the outputs of two maps. In [42], Hua et al. design a two-dimensional (2-D) Logistic-Sine-coupling map (LSCM) and use it as a source of PRNS controlling basic encryption operations of an image encryption scheme, whose structure follows PTDWOS. The same strategy is used in [43], where a spatio-temporal chaotic system is coupled with Tent-Sine system to generate PRNS. In [44], an encryption scheme of protecting medical images with two rounds of position permutation and diffusion, where Logistic-Sine system is used as PRNG.

In [45], the periodicity of Logistic map and its variants over finite field \mathbb{Z}_{3^e} is analyzed. Based on comprehensive analysis of randomness of the PRNS generated by iterating a map, one variant of Logistic map is selected in [45] as a PRNG. In [46], a 6-D discrete chaotic systems (SDDCS) is constructed with some sine and cosine functions, which is then used as a source of PRNS used in a stream cipher. As analyzed in [21], coupled logistic map can demonstrate complex bifurcation dynamics in continuous domain. Actually, the real structure of the final chaotic systems obtained with any above way in digital computer should be analyzed as [47] with the perspective of state-mapping network.

2.1.2. Design of single round PTDWOS

Among the encryption schemes composing of only one round of basic operations, only [12] adopt S-box, where tent map is used as PRNG to control some basic encryption operations on image: modular addition, S-box and binary shift operation.

In [48], 1-round PTDWOS is proposed, where the algorithm on traversing a graph with the strategy of breadth-first search is used to implement position permutation, and a hyperchaotic system is used as PRNG to realize the second permutation and diffusion with XOR (bitwise exclusive OR) and modular addition. In [49], an encryption scheme of image blocks with variable size is proposed, which is composed of position permutation and modulo addition. The two basic operations are controlled by Arnold map and integer Logistic map, respectively. In [50], the proposed image encryption scheme performs only one round of position permutation and XOR operation, which are both controlled by PRNS generated by iterating 2-D Baker's map. The critical frame of the surveillance video for IoT systems is encrypted the two steps designed in [37], where 2-D logistic-adjusted-sine map (LASM) is used as the source of PRNS. The dependence of PRNS on the plain-image can be canceled with a non-negligible probability due to the commutative principle of summation and quantization error of calculating continuous function in finite-precision computer. In [51], a simple fourth-order chaotic system is constructed as PRNG to control the XOR operation and position permutation on a medical image. As only one round of the two basic operations are used, the encryption scheme designed in [51, 37] are both vulnerable to chosen-plaintext attack.

In [52], Ping et al. encrypt two adjacent pixels with position permutation controlled by 2-D Hénon map and modulo addition. In [53], Ping et al. use 2-D LASM to implement the permutation part and 2-D cellular automata as the source of PRNS to control the part on modulo addition. In [54], a PRNG based on a 3-D chaotic map is designed. The framework of the image encryption scheme is the same as that of [53]. In [55], Ping et al. propose a method of digit-level permutation, which can change the histogram of the permuted image. In [22], 2-D Logistic map is used to generate PRNG to control combination of position permutation and diffusion with XOR.

In [56], nine special pixels in the plain-image are selected to generate initial conditions of Lorenz system with Secure Hash Algorithms (SHA-256). However, the sensitivity mechanism can be easily cancelled as only nine selected pixels have no influence on other ones. In [25], a self-adapting colour image encryption scheme based on chaotic maps and the interactions among three channels is proposed. Due to the commutative property of modulo addition, the sensitivity of PRNS relying on the plain-image can be easily cancelled as well.

2.1.3. Design of multiple round PTDWOS

Reference [57] proposes an image encryption scheme based on two rounds of position permutation and XOR operation, which are controlled by PRNSs generated by 2-D

modified Henon map and Sine map, respectively. Reference [58] adopts the same encryption structure as [57] with hardware implementation, where Lorenz chaotic system, Lü's chaotic system and cellular automata are used as the source of PRNS instead. In [59], multiple rounds of PTDWOS are implemented in the level of bit plane, where Skew Tent map is used as source of PRNS. In [4], 2D-SLMM is used to control the two basic part of a scheme following PTDWOS, where modular addition with a fixed matrix is adopted to enhance the diffusion effect. In [60], a bit-level image encryption algorithm is designed by operating multiple rounds of bitwise shift operation and XOR in two directions, where 2D-LICM hyperchaotic map is constructed as the source of PRNG by cascading sine map and Logistic map.

Following the basic structure of AES, a robust image symmetric cryptosystem (RISC) is proposed in [61], where Arnold's cat map is used to generate permutation matrix permuting the entire plain-image. In [62], an image encryption algorithm based on 1-D PWLCM and least squares approximation (LSA) is proposed, where PWLCM is used to determine the permutation relationship among the rows and columns of the plain-image and intermediate matrixes. LSA is used to generate pseudo-random number to mask the permuted intermediate matrixes. In [26], PWLCM is used as PRNG to control combination of two rounds of position permutation and modular addition. In [63], a 2-D partitioned cellular automata is designed to generate PRNS satisfying the global Strict Avalanche Criterion, which is used to control combination of some basic operations including substituting with an S-box.

2.1.4. *Encrypting multiple plain-images simultaneously*

In [3], a double colour image encryption (DCIE) scheme using 3-D Brownian motion is presented, where two colour images are encrypted simultaneously. DCIE follows the structure of PTDWOS and uses 3-D Brownian motion, a 3-D autonomous chaotic system and 2D-LASM as PRNG to control its basic components. In [64], another DCIE using Gyrator transform and Hénon map is proposed. In [65], the four LSB (least significant bit) planes of two images are encrypted by position permutation and value confusion, which are controlled by Logistic map and CA, respectively. In [66], four plain-images are encrypted simultaneously using 2D-LASM. In [67], a sequence of images are simultaneously encrypted and compressed using Tensor Compressive Sensing, which is controlled by PRNS generated by a 3-D discrete Lorenz system. In [68], an encryption scheme encrypting multiple optical colour images is proposed based on phase retrieval in quaternion gyrator domain, nonlinear quaternion correlation is developed to perform authentication.

In [69], an image encryption scheme using beta chaotic map, NSCT (Nonsubsampled Contourlet Transform), and GA (genetic algorithm) is proposed. The plain-image is decomposed into three subbands. GA is used to select the optimized initial parameters of the beta chaotic map for a multiobjective fitness function. Finally, the inverse of NSCT is applied on the encrypted subbands with modulo addition to produce the cipher-image. In [70], teaching learning based optimization algorithm and gravitational search algorithm are used to optimize selection of the parameters. However, such optimization algorithms cost additional unknown computational load. In [71], GA is used to perform parallel permutation and substitution on multiple bit-planes of the plain-image.

2.1.5. *Encrypting images with compressing techniques*

In [72], an image encryption scheme based on compressive sensing and chaotic map were proposed. The 2-D Sine-Logistic modulation map (2D-SLMM) is used in the three basic parts of the scheme: constructing measurement matrix in compression operation; generating PRNG for diffusion operations; producing permutation matrix. In [73], a plain-image is first decomposed by wavelet packet transform (WPT). The WPT coefficients are classified in terms of the average value and Shannon entropy. The coefficients containing principal energy are encrypted by position permutation, modular subtraction and XOR, which are controlled by Logistic map, Chen system and Arnold map, respectively. Other nonzero coefficients are compressed by Compressive sensing with a secret measurement matrix constructed from a Hadamard matrix controlled by Cat map. The encryption scheme is based on 2-D compressive sensing (CS) and FrFT. In [74], Liao et al. employ Kronecker product to generate higher dimensional measurement matrices. In [75], compressive sensing technique is combined with a stream cipher to simultaneously compress and encrypt image and video files, where the measurement matrix is generated using a stream cipher. Only the 4 MSBs of compressed samples are encrypted, which may cause some and even all visual information of the encrypted object revealed.

2.2. *Designing image encryption schemes based on DNA encoding*

With the development of DNA computing, designing image encryption schemes based on DNA encoding received intensive attentions in the past decade [76]. In 2018, about twenty technical papers on the topic were published. Here, we review representative works among them.

In [77], a new heterogeneous chaotic neural network generator was proposed as a source of PRNS to control the

three basic encryption operations on image data: pixel position permutation; DNA-based bit substitution; DNA-based bit permutation. In [78], a robust color image encryption system using Lorenz-Rossler chaotic map and DNA encoding is proposed, where Lorenz-Rossler chaotic map is used as the source for producing PRNS. The three channels of color plain-image and PRNS are transformed into the form of DNA strands. After performing subtraction and addition operations, the results are transformed back to the binary form as the cipher-image. In [79], an image encryption scheme based on DNA encoding and Single Neuron Model (SNM) is designed, using a 2D-LASM and SNM as sources of PRNS. First, the plain-image is encrypted by position permutation and XOR. Then, the intermediate image is further encrypted in the DNA domain with XOR operation.

In [80], a scheme encrypting optical image is designed with the same strategy as that in [77, 79]. In [81], an image encryption scheme using pixel-level scrambling, bit-level scrambling, and DNA encoding is proposed, where a 5-D hyperchaotic system is used as the source of PRNS. In [82], 2-D Hénon-Sine map (2D-HSM) is constructed as a PRNG to control the involved DNA rules, DNA operation and the position permutation. In [83], the saliency detection of a plain-image is detected with a given model and encrypted with a chaos-based encryption function. Then, the encrypted result is embedded into DCT domain of another meaningful nature image as an invisible watermark.

2.3. *Encrypting image in transform domain*

A series of encryption schemes protecting optical images are proposed in 2018. But, most of them are simulated with digital images. In [84], a monospectral SAIL (synthetic aperture integral imaging) system is designed to capture 2-D optical elemental images, which are then XORed with a PRNS generated by CA and encoded by Fresnel transform. In [85], the original image is first scrambled, and then multiplied by the random-phase mask function. A further phase-truncated discrete multiple-parameter FrFT is implemented to realize asymmetric encryption. In [86], a holographic encryption scheme based on interleaving operation of CGHs (computer-generated holograms) is proposed. Using the quaternion algebra, B. Chen et al. defined a multiple-parameter fractional quaternion Fourier transform (MPFrQFT) as a general version of the conventional multiple-parameter fractional Fourier transform (MPFrFT) [87]. Detailed experimental results demonstrate that MPFrQFT is superior to other eight existing algorithms on multiple metrics: key space, key sensitivity, statistical analysis and robustness.

In [88], a DCT-domain image encryption framework is proposed with block-wise permutation and XOR operation,

which is implemented with a stream cipher. In [89], a bitstream-based JPEG image encryption scheme with negligible size expansion is proposed, which cascades four operations: permuting the groups of successive DC codes encoding the differences of quantized DC coefficient with the same sign; swapping the two half parts of a group of consecutive DC codes; scrambling the AC codes falling the same category; randomly shuffling all minimum coded units.

2.4. *Signal processing in the encrypted domain*

In [90], the fast methods on implementing real and complex Walsh-Hadamard Transform in the cipher-images are proposed. To further reduce the computational complexity of the homomorphic encryption operations, two parallelization strategies are given to accelerate the transform. Using strong correlation among neighbouring pixels in a natural image, an effective high-capacity reversible data hiding scheme for encrypted images based on MSB (most significant bit) prediction was proposed in [91]. Interestingly, [91] adopts PWLCM as source producing pseudo-random number sequence, whose randomness is seriously comprised in digital computer [47].

Reversible data hiding in encrypted image (RDH-EI) embeds data into a cipher-image in cloud meanwhile the corresponding plain-image can be perfectly reconstructed by the authorized receiver. In [92], two RDH-EI schemes are proposed with private-key homomorphism and public-key homomorphism, respectively. In [93], an enhanced RDH-EI embedding two bits in each cipher-pixel with minimum distortion of stego-pixel is achieved through homomorphic encryption. In contrast to many data hiding schemes focusing on LSB, an efficient MSB prediction-based method for RDH-EI is proposed in [94], where reserving embedding room before encryption and vacating embedding room after encryption are discussed, respectively. To deal with the compressed images, [95] proposes a separable RDH for encrypted JPEG bitstreams, where the original bitstream is losslessly reconstructed using an iterative recovery algorithm. In [96], a RDH-EI is designed using homomorphic multiplication and probabilistic properties of Paillier cryptosystem, where the embedding room is reserved before encryption.

In [97], C. Wang et al. formulate lossy compression on low-frequency wavelet coefficients as a problem of weighted rate-distortion optimization and solve it by incorporating empirical characteristic of their distribution. In [98], C. Wang et al. propose an iterative reconstruction scheme for compression file of encrypted binary images using the Markov Random Field (MRF) to characterize the corresponding plain-images in the spatial domain. The associate MRF, decryption and decompression based

on LDPC (low-density parity check) are all represented with the methodology of factor graph, a bipartite graph representing the factorization of a function into some sub-functions.

2.5. Generating cipher-images in other application scenarios

- Visual secret sharing

The (k, n) -visual secret sharing (VSS) scheme encode a secret image into n shares, such that any k shares can be superimposed to reveal the secret image to human's eyes but any $k - 1$ or less ones can leak nothing. In [99], three efficient and flexible XOR-based (k, n) -VSS schemes is constructed, such that more than k shares can also reveal the secret image. As for progressive (k, n) secret image sharing (PSIS) scheme, it is required that k to n shares can reconstruct the secret image progressively. In [100], three PSIS schemes are constructed using XOR operation, a variant of Hamming code and modified version of shorten Hamming code, respectively. In [101], an image secret sharing with three decoding options, lossless recovery, grayscale stacking recovery and visual previewing, is designed based on random grid-based VSS and Chinese remainder theorem.

- Privacy-preserving application of image data

In [102], Yuan et al. use similarity degree among encrypted higher-dimensional profile vectors of users images as a metric to search and recommend friends in social media. In [103], a privacy preserving biometrics-based authentication solution is proposed to authenticate the users to remote service providers via zero-knowledge proof of knowledge on two secrets: an identity token encoding the biometric identifier of the user's image and a secret owned by the user. In [104], a searchable symmetric encryption over encrypted multimedia data is proposed by considering the search criteria as a high-dimensional feature vector, which are further mapped by locality sensitive hashing (LSH). The inverted file identifier vectors are encrypted by an additive homomorphic encryption or pseudo-random position permutations. In [105], a privacy-preserving content-based image retrieval (CBIR) scheme is proposed to allow the data owner outsource the image database and CBIR operation to the cloud server without disclosing its actual content. The proposed scheme let the cloud server can solve earth movers distance (EMD) as a linear programming problem without the sensitive information of the searched image.

- Quantum image encryption

The development of quantum cryptography and quantum chaos attracts image presentation in quantum world and study on how to utilize quantum properties for protecting image data [106, 107].

- Permutation against attacks based on "jigsaw puzzle solver"

Due to simplicity and obvious security enhancing effect of position permutation, it is widely used in image encryption scheme [89, 108]. The ciphertext-only attack on any block-wise permutation scheme can be attributed to solving a jigsaw puzzle. Recently, Kiya et al. published a series of works on encrypting each image block with marginal influence on statistics and permuting the encrypted blocks among the whole image. Such encryption-then-compression framework does not seriously influence the further compression and can withstand the attacks based on conventional jigsaw puzzle solvers [109]. But, the correlation among blocks in cipher-images may still facilitate the advanced jigsaw puzzle solvers to optimize the attacking on the block-wise permutation schemes analyzed in [110, 111].

3. Survey on image cryptanalysis

In the year 2018, about 30 papers on image cryptanalysis were published. Among them, the most striking work is depreciating motivation of most chaos-based encryption schemes in [112], refuting any superiority of chaos-based encryption schemes than several variants of AES in terms of computational effort and security performance. In [112], four obviously insecure encryption schemes are subtly constructed to question credibility of the security assessment metrics used in the field of chaotic cryptography widely, e.g. correlation, entropy, histogram variance, Number of Pixel Change Rate (NPCR), Unified Average Changing Intensity (UACI), key sensitivity, robustness against differential attack, sequence test, and NIST randomness test. Considering the quantitative test results of the four special schemes on the metrics, it was concluded that the metrics are far ineffective for security analysis. It was further qualitatively analyzed the inefficiency of the metrics in [1]. Other image cryptanalysis works are separately reviewed in the following three subsections.

3.1. Cryptanalysis of single round PTDWOS

In [113], security of a block-wise image encryption scheme using an ECG signal and the plain-image to determine the used PRNG is analyzed comprehensively. As

the sensitivity mechanism on the plain-image is built via a modulo addition, it can be canceled with a non-negligible probability of $1/256$. Meanwhile, no permutation operation is adopted in the scheme, causing an equivalent secret key can be derived from one pair of a known plain-image and its corresponding cipher-image. As the insecurity of sole permutation analyzed in [114], position permutation is still a simple but efficient measure to improve the security level of the whole encryption scheme.

Four research teams independently studied security analysis of an image encryption scheme using the combination of some 1-D chaotic maps proposed by Pak et al. in 2017, whose structure is one-round PTDWOS with an additional shift permutation. Ignoring the fact that permutation and modulo addition are not commutative, Wang et al. simplifies Pak's scheme by cascading two non-neighbouring permutations together and break it with a chosen-plaintext attack in [16]. The enhanced version of Pak's scheme suggested in [16] is found still vulnerable against chosen-plaintext attack [17]. Assuming a parameter seed is known, the parameter determining the shift permutation of Pak's scheme is disclosed in [18] by its internal properties. Then, Pak's scheme is degenerated into the version analyzed in [16]. Based on the preliminary cryptanalysis works given in [16] and [18], both the equivalent secret-key of Pak's scheme and all its unknown parameters are recovered by a little more pairs of chosen plain-image and the corresponding cipher-image in [19]. In [115], Zhu et al. propose a chosen-plaintext attack on another one-round PTDWOS, where diffusion is implemented by modulo addition and XOR. The equivalent secret key of such diffusion mechanism can be easily recovered [116].

In [15], M. Li et al. propose a chosen-plaintext attack on an image encryption scheme based on Ikeda map, where the Ikeda map is used to generate PRNS to control the mask operation XOR. In [117], M. Li et al. further present two chosen-plaintext attack methods on a colour image encryption using chaotic APFM (Amplitude Phase Frequency Model) nonlinear adaptive filter, which is composed of three parts: position permutation; nonlinear substitution; XOR operation. In [118], M. Li et al. recover the permutation relation of image encryption scheme using PTDWOS with some chosen plain-images. In [119], M. Li et al. recover the equivalent secret key of an encryption algorithm using one-round PTDWOS with 512 pairs of chosen plain-images and the corresponding cipher-images, where hybrid hyper-chaos and cellular automata are used as the source of PRNS to control the permutation and mask operation XOR. In [31], another encryption scheme using PTDWOS is cryptanalyzed. Similar to the strategy given in [113], the sensitivity mechanism of PRNG on the plain-image can be easily cancelled by some special plain-images.

In [32], security defects and chosen-plaintext attack on an image encryption schemes for body area network (BAN) system are analyzed. Furthermore, some additional operations are adopted to withstand the proposed attack: using SHA-512 to build linkage between the plain-image and PRNS; updating initial conditions and control parameters of the chaotic system; adding more complex encryption operations. However, the incurred computational load is not considered for the required security level.

3.2. Cryptanalysis of some image encryption schemes with complex structure

Once the basic encryption operations are repeated some rounds or S-box is used, the structure of the whole encryption scheme become much more complex, which dramatically increases the hardship of the corresponding cryptanalysis.

In [13], two chosen plain-images of fixed value are constructed to recover the equivalent secret key of an "efficient image cryptographic algorithm" reusing the permutation matrix generated by Cat map or Baker map dynamically. But, how to perform the attack on the PTDWOS with multiple rounds are not theoretically proved in [13].

In [120], some special plain-images are selected to narrow the scope of some subkeys of a PTDWOS with less than or equal to 3 rounds. In [121], usability of a 4-round DTPWOS (diffusion-then-permutation without substitution-box) is questioned, which can be considered as a special form of 5-round PTDWOS. Furthermore, the linear relationship between plain-image and the corresponding cipher-image is derived as the adopted permutation is a static rotation of 90 degrees, which is used to support the proposed differential attack. Similar to the strategy introduced in [2], the permutation relation of a multiple-round PTDWOS is recovered by checking how the changes of the cipher-pixels influence that of the plain-pixels in the scenario of chosen-ciphertext attack [122]. In [6], two chosen plain-images are constructed to recover an equivalent version of S-box and PRNS of a chaos-based image encryption scheme using S-box.

3.3. Other image cryptanalysis

According to the scenario or theory used by an encryption scheme, a special cryptanalysis method may work very well.

In [123], a ciphertext-only attack on a double-image optical encryption technique based on an asymmetric (public-key encryption) algorithm is proposed using phase retrieval algorithm with median filtering and normalization operation. As for an optical cryptosystem based on phase-truncated Fourier transform and nonlinear operations, the

same research group presented a specific attack based on phase retrieval algorithm with normalization and a bilateral filter in [124]. In [125], a joint compression and encryption scheme based on elliptic curve cryptography (ECC) is cryptanalyzed. Due to the used parameter of ECC is too small, three known attacking methods on solving elliptic curve discrete logarithmic problem are used to recover the private key from the public key.

In [126], a large number of plaintexts and the corresponding ciphertexts encrypted by any optical encryption technique based on random phase encoding (RPE) are used as training samples for optimizing the parameters of a deep neural network (DNN), which can reconstruct any plain-image from its corresponding cipher-image. Actually, deep learning can also be used to test security of an encryption scheme via adversarial training.

In [33], Luo et al. evaluates the security of chaotic encryption schemes by using side-channel attack. Some intermediate values relating with the plaintext and the round keys can be revealed by observing the power consumption. In [127], influences of different operations on resistance of chaotic image encryption schemes combining position permutation and a mask operation against chosen-plaintext attacks are discussed. Among some reversible and irreversible gates, including XOR, Toffoli and Fredkin gates, only Fredkin gate can facilitate the supported encryption scheme withstand chosen-ciphertext attack (CPA).

About eighty publications on “reversible data hiding in the cipher-image (encrypted domain)” were published in the past decade. Many of them use simple stream cipher XOR to generate cipher-images. Using strong correlation among neighboring bits in every bit-plane in a natural image, a cipher-text only attack is proposed in [34] to recover the approximate version of the original plain-image with good visual quality.

In [128], a chosen-ciphertext attack on a chaotic stream cipher using self-synchronization and closed-loop feedback were proposed. Some parameters of the used 3-D discrete time chaotic system can be estimated. In [129], Lin et al. further derived coefficients of the nominal matrix of a stream cipher based on 8-D self-synchronous chaotic system in the scenarios of known-plaintext attack and CPA, respectively.

4. The challenges on design and analysis of image encryption schemes

Based on the above review on two sides of image cryptology, we summarize some critical challenges on design and security analysis of image encryption schemes as follows.

- No specific application scenario is targeted in the design process of most image encryption schemes. Under such precondition, the balancing point among computation load, the real required security level and economic cost for a potential attack cannot be considered at all. Only a few image encryption schemes are designed for solving security challenge in specific application scenario: surveillance [37], IIoT (industrial Internet of Things) [29], social media [88].
- Special formats of image data are not considered. A large number of image encryption schemes just treat plain-image as an ordinary textual data [5]. Due to the large size of conventional image files, compression and encryption should be combined well [89, 130]. As [131], only ROI (region of interest) of DICOM (Digital Imaging and Communications in Medicine) medical images are encrypted with one round of permutation and substitution to satisfy real-time processing requirement.
- Importance of S-box is seriously neglected. As a lookup table, S-box is an efficient way to obscure the relationship between secret key and the corresponding cipher-image. Strangely enough, it is seldom adopted in image encryption schemes.
- The underlying weak randomness of chaos-based PRNG is widely omitted. The periods of PRNS obtained by iterating Logistic map and skew tent map in digital computer are rigorously analyzed in [47]. Much more theoretical results on dynamical properties of chaotic maps, e.g. 2D-LASM, Hénon map, Lorenz system in limited-precision arithmetic domain should be further investigated by extending the analysis in the field \mathbb{Z}_2 to \mathbb{Z}_{2^e} using advanced theoretical analysis tools, e.g. Hensel’s lifting lemma, where $e > 1$.
- The security test metrics are widely misused. As shown in [112, 113], the security assessment metrics used in most chaos-based image encryption schemes are unconvincing. So convincing methodologies for assessing security of image encryption schemes need to be established urgently.
- The previous lessons drawn by tough cryptanalysis are ignored by the designers of new image encryption schemes. For example, the sensitivity mechanisms of PRNS on the plain-image built in [79, 115, 27, 89] can be easily cancelled by constructing some special plain-images, which has been reported in many cryptanalysis papers such as [1, 113].

- Prejudice on the value of cryptanalysis obstructs the progress of image security. As emphasized in the abstract of the special report on PRNG test suite of NIST, “statistical testing cannot serve as a substitute for cryptanalysis”. It is unreasonable to require a cryptanalyst to propose modifications to withstand the proposed attacks. The work of cryptanalysis should focus on the conditions of required plain-images; computational cost of the attack; space complexity for storing the intermediate data. In 2018, improvement (enhancement, remedy) methods were proposed to fix the reported security defects in many papers on image cryptanalysis as references [6, 13, 14, 15, 16, 17, 18, 19, 20, 30, 32, 115, 127]. In fact, the proposed improvement methods fail to obtain the expected object due to the following subjective and objective reasons:
 - The authors proposing a successful attack, e.g. chosen-plaintext attack in [30], on a given image encryption scheme may not own comprehensive knowledge on designing secure image encryption schemes.
 - Many image encryption schemes are not designed and presented following the basic rules and general guidelines given in [35, 132], which makes essential improvement on the security level of the analyzed schemes very hard.

To cryptanalyze the seemingly complex image encryption scheme (e.g. multi-round PTDWOS), the modern advanced attacking methods in the classic text cryptanalysis should be utilized, especially that published in the top security conferences recently.

5. Conclusion

This paper reviewed the representative works on protecting and attacking image data proposed in 2018 from the viewpoint of a senior image cryptanalyst. The representative works on the two sides were classified and some creative ideas and methods were highlighted. More importantly, the challenges on design and analysis of image encryption schemes were briefly summarized to promote the progress of protection level of image data in cyberspace.

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References

- [1] C. Li, D. Lin, B. Feng, J. Lü, F. Hao, Cryptanalysis of a chaotic image encryption algorithm based on information entropy, *IEEE Access* 6 (2018) 75834–75842. doi:10.1109/ACCESS.2018.2883690.
- [2] E. Y. Xie, C. Li, S. Yu, J. Lü, On the cryptanalysis of Fridrich’s chaotic image encryption scheme, *Signal Processing* 132 (2017) 150–154. doi:10.1016/j.sigpro.2016.10.002.
- [3] Z. Gan, X. Chai, M. Zhang, Y. Lu, A double color image encryption scheme based on three-dimensional brownian motion, *Multimedia Tools and Applications* 77 (21) (2018) 27919–27953. doi:10.1007/s11042-018-5974-9.
- [4] G. Ye, C. Pan, X. Huang, Q. Mei, An efficient pixel-level chaotic image encryption algorithm, *Nonlinear Dynamics* 94 (1) (2018) 745–756. doi:10.1007/s11071-018-4391-y.
- [5] D. dai Liu, W. Zhang, H. Yu, Z. liang Zhu, An image encryption scheme using self-adaptive selective permutation and inter-intra-block feedback diffusion, *Signal Processing* 151 (2018) 130–143. doi:10.1016/j.sigpro.2018.05.008.
- [6] C. Zhu, G. Wang, K. Sun, Cryptanalysis and improvement on an image encryption algorithm design using a novel chaos based s-box, *Symmetry-Basel* 10 (9) (2018) art. no. 399. doi:10.3390/sym10090399.
- [7] H. Liu, A. Kadir, X. Sun, Y. Li, Chaos based adaptive double-image encryption scheme using hash function and S-boxes, *Multimedia Tools and Applications* 77 (1) (2018) 1391–1407. doi:10.1007/s11042-016-4288-z.
- [8] A. Ullah, S. S. Jamal, T. Shah, A novel scheme for image encryption using substitution box and chaotic system, *Nonlinear Dynamics* 91 (1) (2018) 359–370. doi:10.1007/s11071-017-3874-6.
- [9] J. A. Aboites-Gonzalez, J. S. Murguia, M. Mejia-Carlos, H. Gonzalez-Aguilar, M. T. Ramirez-Torres, Design of a strong S-box based on a matrix approach, *Nonlinear Dynamics* 94 (3) (2018) 2003–2012. doi:10.1007/s11071-018-4471-z.
- [10] M. Khan, Z. Asghar, A novel construction of substitution box for image encryption applications with Gingerbreadman chaotic map and s_8 permutation, *Neural Computing & Applications* 29 (4) (2018) 993–999. doi:10.1007/s00521-016-2511-5.
- [11] A. A. Alzaidi, M. Ahmad, M. N. Doja, E. A. Solami, M. M. S. Beg, A new 1d chaotic map and beta-hill climbing for generating substitution-boxes, *IEEE Access* 6 (2018) 55405–55418. doi:10.1109/ACCESS.2018.2871557.
- [12] L. Palacios-Luengas, G. Delgado-Gutierrez, J. A. Diaz-Mendez, R. Vazquez-Medina, Symmetric cryptosystem based on skew tent map, *Multimedia Tools and Applications* 77 (2) (2018) 2739–2770. doi:10.1007/s11042-017-4375-9.
- [13] H. Diab, A. M. El-semary, Cryptanalysis and improvement of the image cryptosystem reusing permutation matrix dynamically, *Signal Processing* 148 (2018) 172–192. doi:10.1016/j.sigpro.2018.02.011.
- [14] J. Wu, X. Liao, B. Yang, Cryptanalysis and enhancements of image encryption based on three-dimensional bit matrix permutation, *Signal Processing* 142 (2018) 292–300. doi:10.1016/j.sigpro.2017.06.014.
- [15] M. Li, H. Fan, Y. Xiang, Y. Li, Y. Zhang, Cryptanalysis and improvement of a chaotic image encryption by first-order time-delay system, *IEEE Multimedia* 25 (3) (2018) 92–101. doi:10.1109/MMUL.2018.112142439.
- [16] H. Wang, D. Xiao, X. Chen, H. Huang, Cryptanalysis and enhancements of image encryption using combination of the 1D chaotic map, *Signal Processing* 144 (2018) 444–452. doi:10.1016/j.sigpro.2017.11.005.
- [17] K. Panwar, R. K. Purwar, A. Jain, Cryptanalysis and improvement of an image encryption scheme using combination of one-

- dimensional chaotic maps, *Journal of Electronic Imaging* 27 (5) (2018) art. no. 053037. doi:10.1117/1.JEI.27.5.053037.
- [18] J. Chen, F. Han, W. Qian, Y.-D. Yao, Z. liang Zhu, Cryptanalysis and improvement in an image encryption scheme using combination of the 1D chaotic map, *Nonlinear Dynamics* 93 (4) (2018) 2399–2413. doi:10.1007/s11071-018-4332-9.
- [19] C. Zhu, G. Wang, K. Sun, Improved cryptanalysis and enhancements of an image encryption scheme using combined 1D chaotic maps, *Entropy* 20 (11) (2018) art. no. 843. doi:10.3390/e20110843.
- [20] W. Feng, Y.-G. He, Cryptanalysis and improvement of the hyperchaotic image encryption scheme based on DNA encoding and scrambling, *IEEE Photonics Journal* 10 (6) (2018) art. no. 7909215. doi:10.1109/JPHOT.2018.2880590.
- [21] A. A. Elsadany, A. M. Yousef, A. Elsonbaty, Further analytical bifurcation analysis and applications of coupled logistic maps, *Applied Mathematics and Computation* 338 (2018) 314–336. doi:10.1016/j.amc.2018.06.008.
- [22] X. Huang, G. Ye, An image encryption algorithm based on irregular wave representation, *Multimedia Tools and Applications* 77 (2) (2018) 2611–2628. doi:10.1007/s11042-017-4455-x.
- [23] J. Ahmad, M. A. Khan, F. Ahmed, J. S. Khan, A novel image encryption scheme based on orthogonal matrix, skew tent map, and xor operation, *Neural Computing & Applications* 30 (12) (2018) 3847–3857. doi:10.1007/s00521-017-2970-3.
- [24] Z. Hua, S. Yi, Y. Zhou, C. Li, Y. Wu, Designing hyperchaotic cat maps with any desired number of positive lyapunov exponents, *IEEE Transactions on Cybernetics* 48 (2) (2018) 463–473. doi:10.1109/TCYB.2016.2642166.
- [25] Y. Luo, R. Zhou, J. Liu, S. Qiu, Y. Cao, An efficient and self-adapting colour-image encryption algorithm based on chaos and interactions among multiple layers, *Multimedia Tools and Applications* 77 (20) (2018) 26191–26217. doi:10.1007/s11042-018-5844-5.
- [26] Y. Zhang, Y. Tang, A plaintext-related image encryption algorithm based on chaos, *Multimedia Tools and Applications* 77 (6) (2018) 6647–6669. doi:10.1007/s11042-017-4577-1.
- [27] S. Kumar, M. Kumar, R. Budhiraja, M. K. Das, S. Singh, A cryptographic model for better information security, *Journal of Information Security and Applications* 43 (2018) 123–138. doi:10.1016/j.jisa.2018.10.011.
- [28] S. Lakshmanan, M. Prakash, C. P. Lim, R. Rakkiyappan, P. Balasubramaniam, S. Nahavandi, Synchronization of an inertial neural network with time-varying delays and its application to secure communication, *IEEE Transactions on Neural Networks and Learning Systems* 29 (1) (2018) 195–207. doi:10.1109/TNNLS.2016.2619345.
- [29] B. Hu, Z.-H. Guan, N. Xiong, H.-C. Chao, Intelligent impulsive synchronization of nonlinear interconnected neural networks for image protection, *IEEE Transactions on Industrial Informatics* 14 (8) (2018) 3775–3787. doi:10.1109/TII.2018.2808966.
- [30] H. Diab, A. M. El-semari, Secure image cryptosystem with unique key streams via hyper-chaotic system, *Signal Processing* 142 (2018) 53–68. doi:10.1016/j.sigpro.2017.06.028.
- [31] H. Fan, M. Li, D. Liu, K. An, Cryptanalysis of a plaintext-related chaotic RGB image encryption scheme using total plain image characteristics, *Multimedia Tools and Applications* 77 (15) (2018) 20103–20127. doi:10.1007/s11042-017-5437-8.
- [32] M. Ahmad, E. A. Solami, X.-Y. Wang, M. N. Doja, M. M. S. Beg, A. A. Alzaidi, Cryptanalysis of an image encryption algorithm based on combined chaos for a BAN system, and improved scheme using SHA-512 and hyperchaos, *Symmetry-Basel* 10 (7) (2018) art. no. 266. doi:10.3390/sym10070266.
- [33] Y. Luo, D. Zhang, J. Liu, Y. Liu, Y. Cao, X. Ding, Cryptanalysis of chaos-based cryptosystem from the hardware perspective, *International Journal of Bifurcation and Chaos* 28 (9) (2018) art. no. 1850114. doi:10.1142/S0218127418501146.
- [34] F. Khelifi, On the security of a stream cipher in reversible data hiding schemes operating in the encrypted domain, *Signal Processing* 143 (2018) 336–345. doi:10.1016/j.sigpro.2017.09.020.
- [35] F. Özkaynak, Brief review on application of nonlinear dynamics in image encryption, *Nonlinear Dynamics* 92 (2) (2018) 305–313. doi:10.1007/s11071-018-4056-x.
- [36] M. Helmy, E.-S. M. El-Rabaie, I. M. Eldokany, F. E. A. El-Samie, Chaotic encryption with different modes of operation based on Rubik’s cube for efficient wireless communication, *Multimedia Tools and Applications* 77 (20) (2018) 27337–27361. doi:10.1007/s11042-018-5923-7.
- [37] K. Muhammad, R. Hamza, J. Ahmad, J. Lloret, H. Wang, S. W. Baik, Secure surveillance framework for IoT systems using probabilistic image encryption, *IEEE Transactions on Industrial Informatics* 14 (8) (2018) 3679–3689. doi:10.1109/TII.2018.2791944.
- [38] Z. Hua, B. Zhou, Y. Zhou, Sine-transform-based chaotic system with FPGA implementation, *IEEE Transactions on Industrial Electronics* 65 (3) (2018) 2557–2566. doi:10.1109/TIE.2017.2736515.
- [39] Z. Hua, Y. Zhou, One-dimensional nonlinear model for producing chaos, *IEEE Transactions on Circuits and Systems I-Regular Papers* 65 (1) (2018) 235–246. doi:10.1109/TCSI.2017.2717943.
- [40] S. Chen, S. Yu, J. Lu, G. Chen, J. He, Design and FPGA-based realization of a chaotic secure video communication system, *IEEE Transactions on Circuits and Systems for Video Technology* 28 (9) (2018) 2359–2371. doi:10.1109/TCSVT.2017.2703946.
- [41] H. Bouslehi, H. Seddik, A new rapid hyperchaotic system for more efficient 2D data encryption, *Multimedia Tools and Applications* 77 (6) (2018) 7741–7762. doi:10.1007/s11042-017-4675-0.
- [42] Z. Hua, F. Jin, B. Xu, H. Huang, 2D logistic-sine-coupling map for image encryption, *Signal Processing* 149 (2018) 148–161. doi:10.1016/j.sigpro.2018.03.010.
- [43] J. Gayathri, S. Subashini, A spatiotemporal chaotic image encryption scheme based on self adaptive model and dynamic keystream fetching technique, *Multimedia Tools and Applications* 77 (19) (2018) 24751–24787. doi:10.1007/s11042-018-5675-4.
- [44] Z. Hua, S. Yi, Y. Zhou, Medical image encryption using high-speed scrambling and pixel adaptive diffusion, *Signal Processing* 144 (2018) 134–144. doi:10.1016/j.sigpro.2017.10.004.
- [45] B. Yang, X. Liao, Some properties of the logistic map over the finite field and its application, *Signal Processing* 153 (2018) 231–242. doi:10.1016/j.sigpro.2018.07.011.
- [46] S. Zhu, C. Zhu, Image encryption algorithm with an avalanche effect based on a six-dimensional discrete chaotic system, *Multimedia Tools and Applications* 77 (21) (2018) 29119–29142. doi:10.1007/s11042-018-6078-2.
- [47] C. Li, B. Feng, S. Li, J. Kurths, G. Chen, Dynamic analysis of digital chaotic maps via state-mapping networks, *IEEE Transactions on Circuits and Systems I: Regular Papers* 66 (5). doi:10.1109/TCSI.2018.2888688.
- [48] Q. Yin, C. Wang, A new chaotic image encryption scheme using breadth-first search and dynamic diffusion, *International Journal of Bifurcation and Chaos* 28 (4) (2018) art. no. 1850047. doi:10.1142/S0218127418500475.
- [49] L. Liu, S. Hao, J. Lin, Z. Wang, X. Hu, S. Miao, Image block encryption algorithm based on chaotic maps, *IET Signal Processing* 12 (1) (2018) 22–30. doi:10.1049/iet-spr.2016.0584.
- [50] B. Mondal, P. Kumar, S. Singh, A chaotic permutation and diffusion based image encryption algorithm for secure communications, *Multimedia Tools and Applications* 77 (23) (2018) 31177–31198. doi:10.1007/s11042-018-6214-z.

- [51] J. Liu, Y. Ma, S. Li, J. Lian, X. Zhang, A new simple chaotic system and its application in medical image encryption, *Multimedia Tools and Applications* 77 (17) (2018) 22787–22808. doi:10.1007/s11042-017-5534-8.
- [52] P. Ping, F. Xu, Y. Mao, Z. Wang, Designing permutation-substitution image encryption networks with Henon map, *Neurocomputing* 283 (2018) 53–63. doi:10.1016/j.neucom.2017.12.048.
- [53] P. Ping, J. Wu, Y. Mao, F. Xu, J. Fan, Design of image cipher using life-like cellular automata and chaotic map, *Signal Processing* 150 (2018) 233–247. doi:10.1016/j.sigpro.2018.04.018.
- [54] M. L. Sahari, I. Boukemara, A pseudo-random numbers generator based on a novel 3D chaotic map with an application to color image encryption, *Nonlinear Dynamics* 94 (1) (2018) 723–744. doi:10.1007/s11071-018-4390-z.
- [55] P. Ping, J. Fan, Y. Mao, F. Xu, J. Gao, A chaos based image encryption scheme using digit-level permutation and block diffusion, *IEEE Access* 6 (2018) 67581–67593. doi:10.1109/ACCESS.2018.2879565.
- [56] Z. Li, C. Peng, L. Li, X. Zhu, A novel plaintext-related image encryption scheme using hyper-chaotic system, *Nonlinear Dynamics* 94 (2) (2018) 1319–1333. doi:10.1007/s11071-018-4426-4.
- [57] S. J. Sheela, K. V. Suresh, D. Tandur, Image encryption based on modified Henon map using hybrid chaotic shift transform, *Multimedia Tools and Applications* 77 (19) (2018) 25223–25251. doi:10.1007/s11042-018-5782-2.
- [58] S. Rajagopalan, S. Rethinam, S. Arumugham, H. N. Upadhyay, J. B. B. Rayappan, R. Amirtharajan, Networked hardware assisted key image and chaotic attractors for secure RGB image communication, *Multimedia Tools and Applications* 77 (18) (2018) 23449–23482. doi:10.1007/s11042-017-5566-0.
- [59] L. Teng, X. Wang, J. Meng, A chaotic color image encryption using integrated bit-level permutation, *Multimedia Tools and Applications* 77 (6) (2018) 6883–6896. doi:10.1007/s11042-017-4605-1.
- [60] C. Cao, K. Sun, W. Liu, A novel bit-level image encryption algorithm based on 2D-LICM hyperchaotic map, *Signal Processing* 143 (2018) 122–133. doi:10.1016/j.sigpro.2017.08.020.
- [61] R. Becheikh, T. Omrani, R. Rhouma, S. Belghith, RISC: a robust image symmetric cryptosystem, *Multimedia Tools and Applications* 77 (19) (2018) 24615–24642. doi:10.1007/s11042-017-5575-z.
- [62] M. Ghebleh, A. Kansa, D. Stvanovic, A novel image encryption algorithm based on piecewise linear chaotic maps and least squares approximation, *Multimedia Tools and Applications* 77 (6) (2018) 7305–7326. doi:10.1007/s11042-017-4634-9.
- [63] Y. Wang, Y. Zhao, Q. Zhou, Z. Lin, Image encryption using partitioned cellular automata, *Neurocomputing* 275 (2018) 1318–1332. doi:10.1016/j.neucom.2017.09.068.
- [64] Z. Shao, Y. Shang, X. Fu, H. Yuan, H. Shu, Double-image cryptosystem using chaotic map and mixture amplitude-phase retrieval in gyration domain, *Multimedia Tools and Applications* 77 (1) (2018) 1285–1298. doi:10.1007/s11042-016-4279-0.
- [65] S. Hanis, R. Amutha, Double image compression and encryption scheme using logistic mapped convolution and cellular automata, *Multimedia Tools and Applications* 77 (6) (2018) 6897–6912. doi:10.1007/s11042-017-4606-0.
- [66] C. Yu, J. Li, X. Li, X. Ren, B. B. Gupta, Four-image encryption scheme based on quaternion fresnel transform, chaos and computer generated hologram, *Multimedia Tools and Applications* 77 (4) (2018) 4585–4608. doi:10.1007/s11042-017-4637-6.
- [67] Q. Wang, M. Wei, X. Chen, Z. Miao, Joint encryption and compression of 3D images based on tensor compressive sensing with non-autonomous 3D chaotic system, *Multimedia Tools and Applications* 77 (2) (2018) 1715–1734. doi:10.1007/s11042-017-4349-y.
- [68] Z. Shao, Y. Shang, Q. Tong, H. Ding, X. Zhao, X. Fu, Multiple color image encryption and authentication based on phase retrieval and partial decryption in quaternion gyration domain, *Multimedia Tools and Applications* 77 (19) (2018) 25821–25840. doi:10.1007/s11042-018-5818-7.
- [69] M. Kaur, V. Kumar, Beta chaotic map based image encryption using genetic algorithm, *International Journal of Bifurcation and Chaos* 28 (11) (2018) art. no. 1850132. doi:10.1142/S0218127418501328.
- [70] S. Noshadian, A. Ebrahimzade, S. J. Kazemitabar, Optimizing chaos based image encryption, *Multimedia Tools and Applications* 77 (19) (2018) 25569–25590. doi:10.1007/s11042-018-5807-x.
- [71] S. Mozaffari, Parallel image encryption with bit-plane decomposition and genetic algorithm, *Multimedia Tools and Applications* 77 (19) (2018) 25799–25819. doi:10.1007/s11042-018-5817-8.
- [72] H. Huang, X. He, Y. Xiang, W. Wen, Y. Zhang, A compression-diffusion-permutation strategy for securing image, *Signal Processing* 150 (2018) 183–190. doi:10.1016/j.sigpro.2018.04.014.
- [73] X. Lv, X. Liao, B. Yang, A novel scheme for simultaneous image compression and encryption based on wavelet packet transform and multi-chaotic systems, *Multimedia Tools and Applications* 77 (21) (2018) 28633–28663. doi:10.1007/s11042-018-6013-6.
- [74] D. Zhang, X. Liao, B. Yang, Y. Zhang, A fast and efficient approach to color-image encryption based on compressive sensing and fractional fourier transform, *Multimedia Tools and Applications* 77 (2) (2018) 2191–2208. doi:10.1007/s11042-017-4370-1.
- [75] V. Pudi, A. Chattopadhyay, K.-Y. Lam, Secure and lightweight compressive sensing using stream cipher, *IEEE Transactions on Circuits and Systems II-Express Briefs* 65 (3) (2018) 371–375. doi:10.1109/TCSII.2017.2715659.
- [76] X.-Y. Wang, P. Li, Y.-Q. Zhang, L.-Y. Liu, H. Zhang, X. Wang, A novel color image encryption scheme using DNA permutation based on the Lorenz system, *Multimedia Tools and Applications* 77 (5) (2018) 6243–6265. doi:10.1007/s11042-017-4534-z.
- [77] G. Maddodi, A. Awad, D. Awad, M. Awad, B. Lee, A new image encryption algorithm based on heterogeneous chaotic neural network generator and DNA encoding, *Multimedia Tools and Applications* 77 (19) (2018) 24701–24725. doi:10.1007/s11042-018-5669-2.
- [78] A. Girdhar, V. Kumar, A RGB image encryption technique using Lorenz and Rossler chaotic system on DNA sequences, *Multimedia Tools and Applications* 77 (20) (2018) 27017–27039. doi:10.1007/s11042-018-5902-z.
- [79] N. B. Slimane, N. Aouf, K. Bouallegue, M. Machhout, A novel chaotic image cryptosystem based on DNA sequence operations and single neuron model, *Multimedia Tools and Applications* 77 (23) (2018) 30993–31019. doi:10.1007/s11042-018-6145-8.
- [80] X.-Q. Fu, B.-C. Liu, Y.-Y. Xie, W. Li, Y. Liu, Image encryption-then-transmission using DNA encryption algorithm and the double chaos, *IEEE Photonics Journal* 10 (3) (2018) art. no. 3900515. doi:10.1109/JPHOT.2018.2827165.
- [81] S. Sun, A novel hyperchaotic image encryption scheme based on DNA encoding, pixel-level scrambling and bit-level scrambling, *IEEE Photonics Journal* 10 (2) (2018) art. no. 7201714. doi:10.1109/JPHOT.2018.2817550.
- [82] J. Wu, X. Liao, B. Yang, Image encryption using 2D Hénon-Sine map and DNA approach, *Signal Processing* 153 (2018) 11–23. doi:10.1016/j.sigpro.2018.06.008.
- [83] W. Wen, Y. Zhang, Y. Fang, Z. Fang, Image salient regions encryption for generating visually meaningful ciphertext im-

- age, *Neural Computing & Applications* 29 (3) (2018) 653–663. doi:10.1007/s00521-016-2490-6.
- [84] X. Li, M. Zhao, Y. Xing, et al., Designing optical 3D images encryption and reconstruction using monospectral synthetic aperture integral imaging, *Optics Express* 26 (9) (2018) 11084–11099. doi:10.1364/OE.26.011084.
- [85] G. Ren, J. Han, J. Fu, M. Shan, Asymmetric image encryption using phase-truncated discrete multiple-parameter fractional fourier transform, *Optical Review* 25 (6) (2018) 701–707. doi:10.1007/s10043-018-0464-x.
- [86] D. Kong, L. Cao, X. Shen, H. Zhang, G. Jin, Image encryption based on interleaved computer-generated holograms, *IEEE Transactions on Industrial Informatics* 14 (2) (2018) 673–678. doi:10.1109/TII.2017.2714261.
- [87] B. Chen, M. Yu, Y. Tian, L. Li, D. Wang, X. Sun, Multiple-parameter fractional quaternion fourier transform and its application in colour image encryption, *IET Image Processing* 12 (12) (2018) 2238–2249. doi:10.1049/iet-ipr.2018.5440.
- [88] W. Sun, J. Zhou, S. Zhu, Y. Y. Tang, Robust privacy-preserving image sharing over online social networks (OSNs), *ACM Transactions on Multimedia Computing Communications and Applications* 14 (1) (2018) art. no. 14. doi:10.1145/3165265.
- [89] J. He, S. Huang, S. Tang, J. Huang, JPEG image encryption with improved format compatibility and file size preservation, *IEEE Transactions on Multimedia* 20 (10) (2018) 2645–2658. doi:10.1109/TMM.2018.2817065.
- [90] P. Zheng, J. Huang, Efficient encrypted images filtering and transform coding with walsh-hadamard transform and parallelization, *IEEE Transactions on Image Processing* 27 (5) (2018) 2541–2556. doi:10.1109/TIP.2018.2802199.
- [91] P. Puteaux, W. Puech, An efficient MSB prediction-based method for high-capacity reversible data hiding in encrypted images, *IEEE Transactions on Information Forensics and Security* 13 (7) (2018) 1670–1681. doi:10.1109/TIFS.2018.2799381.
- [92] B. Chen, X. Wu, Y.-S. Wei, Reversible data hiding in encrypted images with private-key homomorphism and public-key homomorphism, *Journal of Visual Communication and Image Representation* 57 (2018) 272–282. doi:10.1016/j.jvcir.2018.11.017.
- [93] R. Bhardwaj, Enhanced encrypted reversible data hiding algorithm with minimum distortion through homomorphic encryption, *Journal of Electronic Imaging* 27 (2) (2018) art. no. 023017. doi:10.1117/1.JEI.27.2.023017.
- [94] P. Puteaux, W. Puech, An efficient MSB prediction-based method for high-capacity reversible data hiding in encrypted images, *IEEE Transactions on Information Forensics and Security* 13 (7) (2018) 1670–1681. doi:10.1109/TIFS.2018.2799381.
- [95] Z. Qian, H. Zhou, X. Zhang, W. Zhang, Separable reversible data hiding in encrypted JPEG bitstreams, *IEEE Transactions on Dependable and Secure Computing* 15 (6) (2018) 1055–1067. doi:10.1109/TDSC.2016.2634161.
- [96] S. Xiang, X. Luo, Reversible data hiding in homomorphic encrypted domain by mirroring ciphertext group, *IEEE Transactions on Circuits and Systems for Video Technology* 28 (11) (2018) 3099–3110. doi:10.1109/TCSVT.2017.2742023.
- [97] C. Wang, D. Xiao, H. Peng, R. Zhang, A lossy compression scheme for encrypted images exploiting Cauchy distribution and weighted rate distortion optimization, *Journal of Visual Communication and Image Representation* 51 (2018) 122–130. doi:10.1016/j.jvcir.2018.01.007.
- [98] C. Wang, J. Ni, X. Zhang, Q. Huang, Efficient compression of encrypted binary images using the markov random field, *IEEE Transactions on Information Forensics and Security* 13 (5) (2018) 1271–1285. doi:10.1109/TIFS.2017.2784379.
- [99] S. J. Shyu, XOR-based visual cryptographic schemes with monotonously increasing and flawless reconstruction properties, *IEEE Transactions on Circuits and Systems for Video Technology* 28 (9) (2018) 2397–2401. doi:10.1109/TCSVT.2017.2707923.
- [100] Y.-X. Liu, C.-N. Yang, S.-Y. Wu, Y.-S. Chou, Progressive (k, n) secret image sharing schemes based on boolean operations and covering codes, *Signal Processing-Image Communication* 66 (2018) 77–86. doi:10.1016/j.image.2018.05.004.
- [101] X. Yan, Y. Lu, L. Liu, J. Liu, G. Yang, Chinese Remainder Theorem-based two-in-one image secret sharing with three decoding options, *Digital Signal Processing* 82 (2018) 80–90. doi:10.1016/j.dsp.2018.07.015.
- [102] X. Yuan, X. Wang, C. Wang, A. C. Squicciarini, K. Ren, Towards privacy-preserving and practical image-centric social discovery, *IEEE Transactions on Dependable and Secure Computing* 15 (5) (2018) 868–882. doi:10.1109/TDSC.2016.2609930.
- [103] H. Gunasinghe, E. Bertino, Privbiomtauth: privacy preserving biometrics-based and user centric protocol for user authentication from mobile phones, *IEEE Transactions on Information Forensics and Security* 13 (4) (2018) 1042–1057. doi:10.1109/TIFS.2017.2777787.
- [104] Q. Wang, M. He, M. Du, S. S. M. Chow, R. W. F. Lai, Q. Zou, Searchable encryption over feature-rich data, *IEEE Transactions on Dependable and Secure Computing* 15 (3) (2018) 496–510. doi:10.1109/TDSC.2016.2593444.
- [105] Z. Xia, Y. Zhu, X. Sun, Z. Qin, K. Ren, Towards privacy-preserving content-based image retrieval in cloud computing, *IEEE Transactions on Cloud Computing* 6 (1) (2018) 276–286. doi:10.1109/TCC.2015.2491933.
- [106] N. Zhou, X. Yan, H. Liang, X. Tao, G. Li, Multi-image encryption scheme based on quantum 3D arnold transform and scaled zongtang chaotic system, *Quantum Information Processing* 17 (12) (2018) art. no. 338. doi:10.1007/s11128-018-2104-6.
- [107] M. Khan, H. M. Waseem, A novel image encryption scheme based on quantum dynamical spinning and rotations, *Plos One* 13 (11) (2018) art. no. e0206460. doi:10.1371/journal.pone.0206460.
- [108] C. Li, D. Lin, J. Lü, Cryptanalyzing an image-scrambling encryption algorithm of pixel bits, *IEEE MultiMedia* 3 (2017) 64–71. doi:10.1109/MMUL.2017.3051512.
- [109] T. Chuman, H. Kiya, Security evaluation for block scrambling-based image encryption including JPEG distortion against jigsaw puzzle solver attacks, *IEICE Transactions on Fundamentals of Electronics Communications and Computer Sciences E101A* (12) (2018) 2405–2408. doi:10.1587/transfun.E101.A.2405.
- [110] S. Imaizumi, H. Kiya, A block-permutation-based encryption scheme with independent processing of RGB components, *IEICE Transactions on Information and Systems E101-D* (12) (2018) 3150–3157. doi:10.1587/transinf.2018EDT0002.
- [111] C. Li, Cracking a hierarchical chaotic image encryption algorithm based on permutation, *Signal Processing* 118 (2016) 203–210. doi:10.1016/j.sigpro.2015.07.008.
- [112] M. Preishuber, T. Huetter, S. Katzenbeisser, A. Uhl, Depreciating motivation and empirical security analysis of chaos-based image and video encryption, *IEEE Transactions on Information Forensics and Security* 13 (9) (2018) 2137–2150. doi:10.1109/TIFS.2018.2812080.
- [113] C. Li, D. Lin, J. Lü, F. Hao, Cryptanalyzing an image encryption algorithm based on autoblocking and electrocardiography, *IEEE MultiMedia* 25 (4) (2018) 46–56. doi:10.1109/MMUL.2018.2873472.
- [114] L. Zhang, Y. Liu, C. Wang, J. Zhou, Y. Zhang, G. Chen, Improved known-plaintext attack to permutation-only multimedia ciphers, *Information Sciences* 430-431 (3) (2018) 228–239. doi:10.1016/j.ins.2017.11.021.
- [115] C. Zhu, K. Sun, Cryptanalyzing and improving a novel color image encryption algorithm using RT-enhanced

- chaotic tent maps, *IEEE Access* 6 (2018) 18759–18770. doi:10.1109/ACCESS.2018.2817600.
- [116] L. Y. Zhang, Y. Liu, F. Pareschi, Y. Zhang, K.-W. Wong, R. Rovatti, G. Setti, On the security of a class of diffusion mechanisms for image encryption, *IEEE Transactions on Cybernetics* 48 (4) (2018) 1163–1175. doi:10.1109/TCYB.2017.2682561.
- [117] H. Fan, M. Li, D. Liu, E. Zhang, Cryptanalysis of a colour image encryption using chaotic APFM nonlinear adaptive filter, *Signal Processing* 143 (2018) 28–41. doi:10.1016/j.sigpro.2017.08.018.
- [118] M. Li, Y. Guo, J. Huang, Y. Li, Cryptanalysis of a chaotic image encryption scheme based on permutation-diffusion structure, *Signal Processing-Image Communication* 62 (2018) 164–172. doi:10.1016/j.image.2018.01.002.
- [119] M. Li, D. Lu, W. Wen, H. Ren, Y. Zhang, Cryptanalyzing a color image encryption scheme based on hybrid hyper-chaotic system and cellular automata, *IEEE Access* 6 (2018) 47102–47111. doi:10.1109/ACCESS.2018.2867111.
- [120] M. Farajallah, S. El Assad, O. Deforges, Cryptanalyzing an image encryption scheme using reverse 2-dimensional chaotic map and dependent diffusion, *Multimedia Tools and Applications* 77 (21) (2018) 28225–28248. doi:10.1007/s11042-018-6015-4.
- [121] S. Dhall, S. K. Pal, K. Sharma, Cryptanalysis of image encryption scheme based on a new 1D chaotic system, *Signal Processing* 146 (2018) 22–32. doi:10.1016/j.sigpro.2017.12.021.
- [122] T. M. Hoang, H. X. Thanh, Cryptanalysis and security improvement for a symmetric color image encryption algorithm, *Optik* 155 (2018) 366–383. doi:10.1016/j.ijleo.2017.10.072.
- [123] Y. Xiong, A. He, C. Quan, Security analysis of a double-image encryption technique based on an asymmetric algorithm, *Journal of the Optical Society of America A—Optics Image Science and Vision* 35 (2) (2018) 320–326. doi:10.1364/JOSAA.35.000320.
- [124] Y. Xiong, A. He, C. Quan, Cryptanalysis of an optical cryptosystem based on phase-truncated fourier transform and nonlinear operations, *Optics Communications* 428 (2018) 120–130. doi:10.1016/j.optcom.2018.07.058.
- [125] K. M. Singh, L. D. Singh, T. Tuithung, Cryptanalysis of multimedia encryption using elliptic curve cryptography, *Optik* 168 (2018) 370–375. doi:10.1016/j.ijleo.2018.04.068.
- [126] H. Hai, M. Liao, D. Lu, W. He, X. Peng, Cryptanalysis on double random phase encoding with deep learning, in: *Optics and Photonics for Information Processing XII*, 2018, p. art. no. 107510W. doi:10.1117/12.2319902.
- [127] M. H. Annaby, H. Ayad, M. A. Rushdi, On security of image ciphers based on logic circuits and chaotic permutations, *Multimedia Tools and Applications* 77 (16) (2018) 20455–20476. doi:10.1007/s11042-017-5439-6.
- [128] Z. Lin, G. Wang, X. Wang, S. Yu, J. Lü, Security performance analysis of a chaotic stream cipher, *Nonlinear Dynamics* 94 (2) (2018) 1003–1017. doi:10.1007/s11071-018-4406-8.
- [129] Z. Lin, S. Yu, X. Feng, J. Lü, Cryptanalysis of a chaotic stream cipher and its improved scheme, *International Journal of Bifurcation and Chaos* 28 (7) (2018) art. no. 1850086. doi:10.1142/S0218127418500864.
- [130] P. Li, K.-T. Lo, A content-adaptive joint image compression and encryption scheme, *IEEE Transactions on Multimedia* 20 (8) (2018) 1960–1972. doi:10.1109/TMM.2017.2786860.
- [131] M. Noura, H. Noura, A. Chehab, M. M. Mansour, L. Sleem, R. Couturier, A dynamic approach for a lightweight and secure cipher for medical images, *Multimedia Tools and Applications* 77 (23) (2018) 31397–31426. doi:10.1007/s11042-018-6051-0.
- [132] G. Álvarez, S. Li, Some basic cryptographic requirements for chaos-based cryptosystems, *International Journal of Bifurcation and Chaos* 16 (8) (2006) 2129–2151. doi:10.1142/S0218127406015970.