FPGA Implementation of a Chaos-based Stream Cipher and Evaluation of its Performances

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Abstract

Chaos based stream cipher (CSC) has caught the attention of various security applications, especially for military needs and protection in Internet of Things (IoT). In fact, computing and memory resources have been suited by chaos-based stream cipher for real-time communication. In this paper, we designed a chaos-based stream cipher using a robust pseudo chaotic number generator (RPCNG). The simulation of the proposed CSC is done in VHDL using the ISE Design Suite 14.6 tool of Xilinx with finite computing precision $N = 32$ -bit and the hardware implementation is realized on the SAKURA-G FPGA board. The proposed system requires 6036 slices LUTs as hardware cost and achieves throughput of 301.184 Mbps. It is robust against statistical attacks and thus can be used in all applications that require confidentiality.

1. Introduction

The transfer of multimedia data (texts, images, videos, etc.) is growing exponentially and requires reliable techniques to ensure the confidentiality, integrity and authenticity of the data. Data encryption and steganography are the techniques used to achieve confidentiality. The steganography technique is only used when the encryption technique is prohibited (for example in the case of dictatorships in certain countries). In addition, steganography allows dissimulating only small, secret messages compared to the size of the cover medium. Thus, for huge data it is necessary to use symmetric encryption techniques such as block or stream cipher. Block ciphers operate on fixed blocks transformation of plaintext and allows various modes of encryption. Generally, they are more secure than

stream ciphers, however, they are more complex in software and hardware implementation and thus they have less computational performance compared to stream ciphers. Stream ciphers operate continuously on clear text sequences (sample by sample) so they are more suitable for communication data and have better computational complexity compared to block ciphers.

Consequently, in September 2008, the e-STREAM project finally proposed seven stream ciphers, which are considered to be secure and fast. They are practically used as standard of stream ciphers [1]. Alternatively, in the literature, several works have proposed stream encryption based on chaotic systems implemented by software [2], [3], [4]. Indeed, such cryptosystems have a strong nonlinearity compared to standard cryptography and intrinsically there is randomness in the produced chaotic sequences. The chaotic signal is presented as noise but is fully reproducible due to the deterministic mathematical model used. Such cryptosystems can provide a good combination of high security and computational performance. Furthermore, the designing of chaos-based cryptosystems is easier than designing standard cryptosystems.

In this paper, we propose and realize an effective hardware implementation on a FPGA board of a stream cipher based on Robust Pseudo-Chaotic Numbers Generator (RPCNG). The results obtained by the proposed system are compared to some published works [5], [6], [7]. The structure of the paper is arranged as follows: section 2 describes the design and the hardware implementation of the proposed chaos-based stream cipher as well as its hardware metrics performance; section 3 provides the security analysis of the system and section 4 summarizes the whole paper.

Figure 1. Block diagram of stream cipher

2. Hardware implementation of the proposed CSC

The architecture of the proposed chaos-based stream cipher is presented in Figure 1.

The key stream K_i produced by the chaotic system is xored with the plaintext P_i (any kind of data: text, image, video to protect) for generating the cipher text C_i (data protected) as showed by equation 1:

$$C_i = P_i \oplus K_i \quad (1)$$

2.1. Description of the chaotic key stream generator

The proposed key stream generator of Figure 1 is an improved architecture compared to those given in our previous works [8] and [9]. In this architecture, in addition of the discrete Logistic and Skew-Tent map we integrate the discrete 3-D Chebyshev map. The 3-D Chebyshev map allows greater robustness against algebraic attack. The three discrete chaotic maps are weakly coupled and the key stream is generated by combination of the three-coupled outputs. The secret key K of the system is constituted by:

- The initial conditions XL , XS and XT of the three chaotic maps: Logistic, Skew-Tent and 3-D Chebyshev map respectively, each ranging from 1 to $2^N - 1$.
- The control parameter P_s of Skew-Tent map, in the range $[1; 2N - 1]$ and the coupling parameters ϵ_{ij} , ranging from $[1; 2k]$ and $k \leq 5$.

Discrete Logistic map:

$$XL(n) = F_L[XL(n-1)] = \begin{cases} \left\lfloor \frac{XL(n-1)[2^N - XL(n-1)]}{2^{N-2}} \right\rfloor & \text{if } XL(n-1) \neq [3 \times 2^{N-2}, 2^N] \\ 2^N - 1 & \text{otherwise} \end{cases} \quad (5)$$

The initial values $XL(0)$, $XS(0)$ and $XT(0)$ of the used chaotic maps are calculated as follows:

$$\begin{cases} XL(0) = XL \oplus IVL \\ XS(0) = XS \oplus IVS \\ XT(0) = XT \oplus IVT \end{cases} \quad (2)$$

Where IVL , IVS and IVT are provided by the initial value IV . The output samples $XL(n)$, $XS(n)$ and $XT(n)$ of the coupled matrix M are used to produce the output sequence $X(n)$ as showed in Figure 1. The internal system is governed by the following equation:

$$\begin{bmatrix} XL(n) \\ XS(n) \\ XT(n) \end{bmatrix} = M \times \begin{bmatrix} F_L[XL(n-1)] \\ F_S[XS(n-1), P_s] \\ F_T[XT(n-1)] \end{bmatrix} \quad (3)$$

Where M represent the weak coupling matrix and given by:

$$M = \begin{bmatrix} M_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{21} & M_{22} & \epsilon_{23} \\ \epsilon_{31} & \epsilon_{32} & M_{33} \end{bmatrix} \quad (4)$$

With $M_{11} = (2^N - \epsilon_{12} - \epsilon_{13})$, $M_{22} = (2^N - \epsilon_{21} - \epsilon_{23})$, $M_{33} = (2^N - \epsilon_{31} - \epsilon_{32})$, and $F_L[XL(n-1)]$, $F_S[XS(n-1), P_s]$, and $F_T[XT(n-1)]$ are the three nonlinear chaotic functions producing samples at instant n from samples at instant $(n-1)$. They are respectively defined as follows:

Discrete Skew-Tent map:

$$XS(n) = F_s[XS(n-1), P_s] = \begin{cases} \left\lfloor \frac{2^N \times XS(n-1)}{P_s} \right\rfloor & \text{if } 0 < XS(n-1) < P_s \\ \left\lfloor 2^N \times \frac{2^N - XS(n-1)}{2^N - P_s} \right\rfloor & \text{if } P_s < XS(n-1) < 2^N \\ 2^N - 1 & \text{otherwise} \end{cases} \quad (6)$$

Discrete 3-D Chebyshev map:

$$XT(n) = F_t[XT(n-1)] = \left\lfloor 2^{(-2N+2)} \times \left(4 \times (XT - 2^{(N-1)})^3 - 3 \times 2^{(2N-2)} \times (XT - 2^{(N-1)}) \right) + 2^{(N-1)} \right\rfloor \quad (7)$$

We present below the main statistical properties (histogram uniformity and NIST test) of each chaotic map used alone: Logistic, Skew-Tent and 3-D Chebyshev map, as base of the proposed chaos based stream ciphers. The chaotic maps are discretized making them run over a finite precision $N = 32$.

First, we have plotted in Figures 2, 3, and 4 the histograms of the generated sequences $XL(n)$, $XS(n)$, and $XT(n)$ respectively. Visually, the generated sequences are not uniform over all the values $[1, 2^{32} - 1]$.

Figure 2. Histogram of the sequence $XL(n)$ generated by the discrete Logistic map

Figure 3. Histogram of the sequence $XS(n)$ generated by the discrete Skew-Tent map

Figure 4. Histogram of the sequence $XT(n)$ generated by the discrete 3-D Chebyshev map

We confirm the non-uniformity of these sequences using the Chi-square test. The experimental Chi-square χ^2 value is given by:

$$\chi_{exp}^2 = \sum_{i=0}^{N-1} \frac{(O_i - E_i)^2}{E_i} \quad (8)$$

Where $N = 1000$ is the number of classes, O_i is the number of calculated samples in the i th class E_i , and $E_i = 10^8/N$ is the expected number of samples of a uniform distribution.

Table 1, gives the results obtained of the Chi-square test. The calculated experimental value χ_{exp}^2 is higher than the theoretical one χ_{th}^2 . This asserts the non-uniformity of the histograms of sequences $XL(n)$, $XS(n)$, and $XT(n)$.

Table 1. Chi-square test

Chi-Square test (1000, 0.05)	χ_{th}^2	χ_{exp}^2	Result
Logistic map	1073.64	3990034.96	not uniform
Skew-Tent map	1073.64	1171.35	not uniform
3-D Chebyshev map	1073.64	4234181.41	not uniform

Second, we apply the NIST statistical test by generating 100 different sequences, each of size equal to 3,125,000 samples and using different secret key for each sequence. In Figure 5, 6, and 7 we present the results obtained of the NIST test.

Figure 5. NIST test results of the Logistic map

Figure 6. NIST test results of the Skew-Tent map

Figure 7. NIST test results of the 3-D Chebyshev map

Obtained results show that sequences $XL(n)$, $XS(n)$, and $XT(n)$ does not pass all the NIST tests. Also, we remark that the Skew-Tent map has better NIST performance than the other studied chaotic maps: Logistic and 3-D Chebyshev map.

2.2. Hardware implementation and evaluation of the proposed CSC

The design was coded in hardware descriptive language (VHDL). Units such as dividers, multipliers, subtractors and adders in fixed point arithmetic representation are used in FPGA-based implementation of the proposed stream cipher. The multiplication and division processes are a bit more complex and generally they require a much more complex logic circuits. For this reason, we try to avoid their use whenever possible, unless there are special cases. Therefore, to achieve an efficient division or multiplication by 2^n , we apply the following known rule: in binary representation shifting to the right of n positions corresponds to a division by 2^n and shifting to the left of n positions corresponds to a multiplication by 2^n . For the implementation of the proposed stream cipher, we used the ISE Design Suite 14.6 tool of Xilinx. This tool constitutes an efficient design environment, which brings together all the necessary mechanisms for the implementation of a digital circuit, ranging from behavioral description in VHDL to generation of the corresponding diagram in logic gates. Table 2 summarizes the hardware resources occupied by the proposed CSC following the synthesis and implementation processes.

The implementation uses 272 slice registers, 6,036 slice Look Up Tables (LUTs) and 27 DSP blocks. It produces one sample at each clock cycle and the throughput obtained is 301.184 Mbps for a clock frequency of 9.412 MHz. Table 3 provides a summary of the frequency, throughput and resource uses for the implementation of the proposed encryption algorithm, also a comparative result obtained by some published stream ciphers and implemented on FPGA platforms.

Table 2. Usage statistics for xilinx spartan6 xc6slx75-2-csg484 chip of the proposed FPGA based stream cipher

Device utilization summary	
Logic Utilization	Used / utilization %
Number of Slice Registers	272 / 1
Number of Slice LUTs	6036 / 12
Number of occupied Slices	1733 / 14
Number of bonded IOBs	21 / 6
Number of DSP48A1s	27 / 20

From the results given in Table 3, we can notice that the proposed CSC has satisfactory performance compared to the other mentioned hardware implementations of stream ciphers. However, this comparison remains relative, since the hardware implementations considered are not made all on the same FPGA platform.

Table 3. Comparison of hardware metrics with some published works

Hardware metrics	Ref			
	[5]	[6]	[7]	Proposed
LUTs	2363	2718	1169	6036
FFs	-	791	416	231
Frequency (MHz)	18.5	15.598	89.27	9.412
Throughput (Mbps)	565	124	1178	301.184

3. Security analysis of the proposed CSC

In what follows, we present the key space and statistical analysis obtained from the proposed chaotic system.

3.1. Key space analysis

The size of the secret key of a given cryptosystem is the total of initial conditions and parameters of the cryptosystem. Since, the size of the secret key is linked directly to the security level of a symmetric cryptosystem, it is recommended to use secret keys of size typically larger than 128 bits to resist against brute force attacks. Indeed, the integration of three chaotic maps in the proposed cryptosystem allows, on the one hand, to increase the size of the secret key and, on the other hand, to improve the quality of the generated sequences. The size of the secret key of the proposed stream cipher is given by:

$$K = XL + XS + P_s + XT + (6 \times \epsilon_{ij}) = 158 \text{ bits} \quad (8)$$

Where the size of XL , XS , XT and P_s is equal to 32 bits each and the size of ϵ_{ij} is equal to 5 bits. The key space of the secret key is 2^{158} different combinations. Therefore, the size of the secret key used for image encryption is large enough to make brute force attack impossible.

3.2. Statistical Analysis

The majority of statistical attacks against stream cipher algorithms aim to detect and exploit the weaknesses linked to the key stream generators used, through the statistical analysis on the key stream sequences K_i and cipher sequences C_i . In this regard, firstly we used the standard NIST SP 800-22 tests [10] to evaluate the statistical properties of the proposed PCNG. All the tests are applied to 100 key stream sequences K_i of a total size equal to 10^8 bits, generated from 100 secret keys. The results show in Table 4 indicate that the sequences produced by the proposed generator pass all the statistical tests with

success. This means that the proposed PCNG produces pseudo random sequences.

Secondly, we tested the confusion property on five ciphered images, whose plain images are of different natures. The results obtained on the one hand, on the ciphered images given in Figures 8 to 12 c and their histograms presented in Figures 8 to 12 d and on the other hand, the entropy and correlation measurements given in Table 6 indicate the good level of confusion.

Indeed, as we can see, from Figures 8 to 12 d that the histograms of the encrypted images visually seem to be distributed uniformly compared to the histograms of the plain images showed in Figures 8 to 12 b.

To assert the uniformity of the encrypted image histograms, we apply the chi-square test. As we can see from Table 5, the experimental chi-square values are smaller than the theoretical ones, confirming thus the uniformity.

Furthermore, it is clear from Table 6 that, for the encrypted images, the information entropy is close to the optimal value 8 and the correlation coefficient is close to zero, which proves that there is no correlation between the plain and ciphered images. Whereas for the plain images, the correlation coefficient is close to one, which indicates that, the pixels are highly correlated. Moreover, these results are confirmed in Figures 13-14 that shows the correlation of horizontally, vertically and diagonally adjacent pixels in the plain and ciphered Cameraman and Pepper images. Similar results are obtained for Flowers, Gold hill and Kiel images.

Therefore, there is no similarity between the original and encrypted images.

Table 4. P-values and proportion results of nist test for the proposed pcng

Test	P-value	Proportion %
Frequency test	0.367	99
Block-frequency test	0.699	100
Cumulative-sums test (2)	0.768	99
Runs test	0.367	100
Longest-run test	0.740	100
Rank test	0.616	99
FFT test	0.122	98
Non-periodic-templates (148)	0.514	98.980
Overlapping-templates	0.936	97
Universal	0.514	98
Approximate Entropy	0.367	100
Random-excursions (8)	0.386	98.785
Random-excursion-variant (18)	0.527	97.994
Serial test (2)	0.526	99.5
Linear-complexity	0.262	100

Table 5. Theoretical and experimental values for the chi-square test

Chi-Square test (256, 0.05)	χ_{th}^2	χ_{exp}^2
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Cameraman	293.24	266.68
Pepper	293.24	231.84
Flowers	293.24	253.28

Gold hill	293.24	221.64
Kiel	293.24	218.18

Figure 8. Result of Cameraman image. (a) Plain image, (b) Histogram of plain image, (c) Encrypted image, and (d) Histogram of encrypted image.

Figure 9. Result of Pepper image. (a) Plain image, (b) Histogram of plain image, (c) Encrypted image, and (d) Histogram of encrypted image.

Figure 10. Result of Flowers image. (a) Plain image, (b) Histogram of plain image, (c) Encrypted image, and (d) Histogram of encrypted image.

Figure 11. Result of Gold hill image. (a) Plain image, (b) Histogram of plain image, (c) Encrypted image, and (d) Histogram of encrypted image.

Figure 12. Result of Kiel image. (a) Plain image, (b) Histogram of plain image, (c) Encrypted image, and (d) Histogram of encrypted image.

Figure 13. Correlation of adjacent pixels for Cameraman and encrypted Cameraman image in horizontal, vertical and diagonal direction

Figure 14. Correlation of adjacent pixels for Pepper and encrypted Pepper image in horizontal, vertical and diagonal direction.

4. Conclusion

In summary, we have shown and commented on the various results obtained related to the hardware implementation of the proposed chaos-based stream cipher that we implemented on a Spartan-6 xc6slx75-2-csg484 FPGA, using the VHDL description. From these results, we can conclude that the proposed algorithm resists against statistical and brute force attack. In addition, it has a satisfactory performance in terms of hardware metrics.

Table 6. Entropy analysis and correlation coefficient values of the plain and ciphered images

Test image	Entropy	Correlation coefficient		
		<i>Horizontal</i>	<i>Vertical</i>	<i>Diagonal</i>
Cameraman	7.0014	0.9024	0.9360	0.8876
Cameraman encrypted	7.9550	0.0011	-0.0090	0.0016
Pepper	7.5939	0.9599	0.9679	0.9404
Pepper encrypted	7.9580	-0.0028	-0.0059	0.0015
Flowers	7.3710	0.9236	0.9493	0.8935
Flowers encrypted	7.9555	-0.0002	-0.0029	0.0011
Gold hill	7.5678	0.9703	0.9722	0.9530
Gold hill encrypted	7.9539	-0.0051	-0.0002	-0.0002
Kiel	6.8502	0.9183	0.8861	0.8369
Kiel encrypted	7.9568	-0.0012	-0.0019	-0.0003

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