

Cryptanalysis of Shi's White-box Encryption Scheme

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This work has supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NO. 2021M1A2A2043893)

ABSTRACT Structural analysis is the study of finding component functions for a given function. In this paper, we proceed with structural analysis of structures consisting of the S (nonlinear Substitution) layer and the A (Affine or linear) layer. Our main interest is the $S^{(2)} \circ A \circ S^{(1)}$ structure with different substitution layers and large input/output sizes. The purpose of our structural analysis is to find the functionally equivalent oracle F^* and its component functions for a given encryption oracle $F = S^{(2)} \circ A \circ S^{(1)}$. As a result, we can construct the decryption oracle F^{*-1} explicitly and break the one-wayness of the building blocks used in a White-box implementation. Our attack consists of two steps: S layer recovery using multiset properties and A layer recovery using differential properties. We present the attack algorithm for each step and estimate the time complexity. Finally, we discuss the applicability of $S^{(2)} \circ A \circ S^{(1)}$ structural analysis in a White-box Cryptography environment.

INDEX TERMS Cryptanalysis, Structural analysis, White-box cryptography, White-box Implementation

I. INTRODUCTION

CRYPTOGRAPHIC technology is widely used in information and communication services for data protection and authentication. In encryption technology, encryption keys are essential for data and information and communication services authentication.

- Intro. to WBC
- Shi's model
- Structural analysis
- Our contribution

The security of the cryptosystem can be guaranteed only when the encryption key is safely protected from various attackers. The attacker models that threaten the security of cryptosystems include black-box attacks, gray-box attacks, and white-box attacks. The black-box attack is carried out through input and output values in unknown assumptions inside the cryptosystem. The gray-box attack is a technique that acquires and attacks side-channel information such as a cryptographic module's power and electromagnetic waves. Among them, the white-box attack assumes the most potent attacker. The white-box attack is a model in which an attacker takes control of the cryptosystem and neutralizes the cryptography. For example, there are dump and change of memory or register, monitoring the execution process, and

the like. This has attracted attention to protect encryption keys used for copyright protection from exposure in media players and set-top boxes. Currently, the scope of use is expanding due to the safe execution of financial applications in a mobile environment and the prevention of firmware forgery in embedded devices [1]. In 2002, Chow et al [2, 3], suggested the possibility of white-box cryptography of AES (Advanced Encryption Standard) and DES (Data Encryption Standard) along with the concept of white-box attackers, and various white-box cryptography technologies were proposed after that. The security of white-box cryptography generally aims at all or part of preventing exposure to encryption keys, one-wayness of encryption or decryption, and preventing the reproduction of cryptosystems [4]. It was analyzed that most of the white-box cryptography designed in a table reference method, including white-box cryptography such as Chow, does not satisfy any security goals. In general, one-wayness, the security of the white-box, cannot be maintained based on the analysis results of the SASAS structure consisting of the non-linear function S-box and the affine function proposed by Biruykov et al. [6, 7]. The analysis results of structures other than the SASAS structure are also the same. However, various attempts are still underway, and white-box cryptographic products that adopt undisclosed techniques are

also actively spreading [5]. This paper proposes an attack method on the light-weight white-box encryption scheme for securing distributed embedded devices presented by Shi et al. to IEEE Transaction on Computers in 2019 [8]. The LW-WBC (Light-Weight White-Box Cryptography) proposed by Shi et al. has a Feistel structure and protects the input and output value of the XOR (exclusive or) operation by using a table reference method in each round. In addition, it was argued that it was safe against the existing white-box attack method. The LW-WBC, a 60-bit $S^{(1)}AS^{(2)}$ structure with different nonlinear S-box sizes, increases attack complexity and enhances security by not exposing the linear functions used. However, as a result of applying Biruykov's SASAS structural analysis, it was confirmed that the inverse functions of each round could be efficiently obtained [8]. This cannot guarantee one-wayness, which is the security of the white-box cryptography. This paper presents the existing white-box cryptographic model and structural analysis studies. First, we implement LW-WBC based on C language and analyze the security evidence claimed by Shi. After that, we present the structural analysis algorithm of the $S^{(1)}AS^{(2)}$ structure and calculate the attack complexity based on it. Finally, the attack is carried out by applying structural analysis to the LW-WBC using Python language. The results of this study can be used in commercialized white-box cryptographic models with $S^{(1)}AS^{(2)}$ structures.

II. WHITE-BOX CRYPTOGRAPHY AND STRUCTURAL ANALYSIS

White-box cryptographic model uses obfuscation techniques by applying encoding to plaintext, ciphertext, and intermediate values. Various white-box cryptographic model design studies are underway, starting with the symmetric key cryptography AES white-box cryptographic model proposed in 2002 [2]. This white-box cryptographic model is very closely related to cryptographic logic, structural analysis. Structural analysis is a study that started with a different motive than white-box cryptography. This section examines the research trend of the white-box cryptographic model. In addition, we look at the structural analysis research trend closely related to the security of white-box cryptography.

A. RESEARCH TRENDS IN WHITE-BOX CRYPTOGRAPHY

Chow et al. proposed AES' white-box cryptographic model in 2002 and presented a design idea that binds fixed encryption keys into tables, including XOR (exclusive-or) operations. Chow's design ideas are the basis for designing the white-box cryptographic model to date. However, it is not safe with a BGE attack [9], and encryption keys can be extracted by analyzing the table reference method regardless of whether encoding and obfuscation are applied. This is enough to obtain an encryption key from a given table in a few seconds in a PC environment. After that, there have been various studies to supplement Chow's white-box design, but most attack methods have been proposed within

TABLE 1. Designs and Attacks in Whitebox cryptography

Whitebox Cryptography	Design	Attack
Whitebox AES	Chow (2002)	Billet (2004)
Whitebox DES	Chow (2002)	(2007)
Perturbated White-box AES	(2006)	(2010)
White-box AES with large linear encoding	(2009)	(2013)

a few years. Xiao, Lai [10] presented 16-bit, 32-bit linear function encoding to improve the weakness of 4-bit unit non-linear encoding in the table reference method. Still, a linear equivalence transformation attack method was discovered by Mulder et al. [11]. In addition, in 2020, vulnerabilities were found in the method of obfuscating the round boundary and adding dummy rounds proposed by Xu et al. [12]. As shown in TABLE I, research on white-box cryptography, which has been steadily improved in table reference methods, has continued until recently [13].

To overcome the limitations of white-box cryptography for standard cryptography, research is also underway to propose white-box cryptography and a suitable cryptographic algorithm. This started in earnest with introducing the space-hard concept by Bogdanov et al. [14] in 2015. WEM (standing for white-box Even-Mansoor) of Chow et al. [26] proposed a new security concept and operation mode of white-box cryptography. Kwon et al. [27] announced FPL (Feistel cipher using Parallel table Look-ups) block ciphers that combine provable security using parallel table reference methods. Along with developing algorithms suitable for this white-box, the security concept was also discussed from various perspectives. Wyseur [4], Saxena [28] in 2009, and Delerablee et al. [29] in 2013 summarized the security concept that white-box cryptography should satisfy, but most of them are difficult to achieve. In 2020, Bock et al. [30, 31] proposed a security concept considering a practical environment and summarized the security of white-box cryptography based on HW-binding and SW-binding. There are various viewpoints on the security concept and goal of white-box cryptography, and commercial products mainly use private white-box cryptography technology that combines solid obfuscation [5, 32, 33]. The white-box cryptography design is also utilized in SM4, a Chinese standard block cipher algorithm. Various designs and analyses of white-box cryptography are in progress in China. Xiao, Lai [18] and Shang [24] and Yao, Chen [25] designed a white-box cryptography model based on SM4 in 2009, 2016, and 2020, but based on a collision attack, the results were announced that it is difficult to maintain security through the analysis method [19]. As a similar research case, an SM4-based light-weight white-box cryptography model suitable for WSNs (Wireless Sensor Networks) environment was proposed by Shi, Yang et al. in 2015. In 2019, a light-weight white-box cryptographic model suitable for distributed resource systems and combining non-linear and affine functions was proposed [22, 8]. However, a vulnerability in the white-box cryptographic model was

TABLE 2. Structural analysis of Substitution-Affine Iterations

Year	Topic	Authors
2001	Structural cryptanalysis of SASAS	A Biryukov et al.
2003	Affine Equivalence Algorithm	A Biryukov et al.
2015	Structural cryptanalysis of ASASA	I Dinur et al.
2015	Analytic Tools for White-box Cryptography	C.H. Baek et al.
2018	An improved Affine Equivalence Algorithm	I Dinur

discovered in WSNs through collision-based attacks in 2021 [23]. The white-box cryptographic model proposed in 2019 can confirm its applicability to structural analysis attack [7].

B. RESEARCH TRENDS IN STRUCTURAL ANALYSIS

White-box cryptography is closely related to cryptographic logic, structural analysis. In 1997, Paratin et al. [34] attempted to create the function of public-key cryptography by combining S-box, which is the secret key cryptography logic, and higher-order polynomials. However, although it did not yield successful results, it led to a systematic structural analysis study in the future. As shown in TABLE II, security analysis is conducted on functions of various structures in which nonlinear and affine layers (or linear) with multiple S-boxes alternately appear.

Structural analysis is a study of a method of determining each component under conditions in which the structure of a function is known, but the specific function of each component is unknown. In other words, it is a technique of creating an equivalent function having the same function using only the input/output value of a given oracle function. In 2001, Biryukov et al. [6] considered a function of the SASAS structure as an oracle and discovered a way to find an oracle of the same structure with equal functionality. Using this method, you can discover the encryption key hidden inside the SASAS structure. Most of the white-box cryptography using the table reference method can be attacked by this analysis method. The BGE attack [9] can also be interpreted as this analysis method. Baek et al. proposed a toolbox that generalized structural analysis and presented systematic and quantitative attacks on various structures. This structural analysis has expanded its research to various structures such as ASASA and SASASASAS. Typical attacks on white-box cryptography include obtaining encryption keys and attacking one-wayness properties by constructing a decryption algorithm for a given encryption system. White-box cryptography, which combines non-linear and affine functions into tables, is difficult to maintain security through structural analysis. However, various studies are still in progress to design a white-box encryption model based on one-wayness.

III. SHI'S WHITE-BOX ENCRYPTION SCHEME: LW-WBES

In 2019, Shi et al. proposed a white-box encryption scheme for light-weight embedded devices including mobile phones and navigating systems. We denote their scheme by LW-WBES, which means a Light-Weight White-Box Encryption Scheme. LW-WBES has the following features:

- The block size (input/output size) is 120 bits.

- The number of rounds depends on the security level such as 16(default), 10(aggressive), or 32(conservative).
- The encryption process is designed as a variant of Feistel network.
- Two types of keys (black-box key and white-box key) are used for providing black-box security and white-box security simultaneously. Hence, the key size of LW-WBES is extremely large.

A. DESIGN RATIONALE

In order to overcome the difficulties of white-box implementations of standard ciphers, Shi et al. propose a new white-box friendly cipher secure against white-box attack context. Their design strategies can be summarized as follows:

- The scheme has the secret components based on the Feistel network, which protect the secret white-box keys from white-box attacks including DCA and DFA.
- Since components of three different size (4, 5, 6-bit) are integrated, it is hard to mount the structural analysis directly.
- The secret components can be reused in each round for saving memory usage in light-weight devices.
- The scheme does not require additionally external encodings nor obfuscation techniques.

We will show that the goal of design rationale cannot be satisfied and weak against structural cryptanalysis in particular.

B. SPECIFICATION

LW-WBES is a 120-bit block cipher and the number of round can be chosen based on the level of security and the constraints of resources. Here, we describe the encryption process of 16-round default version. 120-bit plaintext $PT = (L, R)$ is input for the Feistel network divided into 5-bit variables as:

$$PT = (L, R) = (L_0, L_1, \dots, L_{11}, R_0, R_1, \dots, R_{11}),$$

where $L_i, R_i \in GF(2)^5$ for $i = 0, 1, \dots, 11$. In each round, the round function $F : GF(2)^{60} \times GF(2)^{72} \rightarrow GF(2)^{72}$ consumes 72-bit black-box round key rk by

$$F : (x, k) \mapsto (\Theta_0(x) \oplus rk_0, \dots, \Theta_{11}(x) \oplus rk_{11}),$$

where Θ_i are nonlinear surjective functions whose outputs are 8-bits and rk is divided into 6-bit components rk_i for $i = 0, 1, \dots, 11$. In fact, we do not need the details of Θ_i to construct our attack algorithm. Instead of usual mixing by exclusive-or in Feistel network, LW-WBES uses non-linear mixing function called T-box which contains white-box key component. The round transformation $(X_L, X_R) \mapsto (Y_L, Y_R)$ can be written as

$$\begin{cases} Y_L = X_R, \\ Y_R = T(X_L, F(X_R, rk)), \end{cases}$$

where T-box $T : GF(2)^{60} \times GF(2)^{72} \rightarrow GF(2)^{60}$ consists of 4 sub-components G, F', H^* , and M is defined as

$$T(x, y) = H^*(M(G(x) \oplus F'(y)))$$

- $G : GF(2)^{60} \rightarrow GF(2)^{60}$ is composed of 12 bijections G_0, G_1, \dots, G_{11} in parallel so that

$$(x_0, x_1, \dots, x_{11}) \xrightarrow{G} (G_0(x_0), G_1(x_1), \dots, G_{11}(x_{11})).$$

- $F' : GF(2)^{72} \rightarrow GF(2)^{60}$ takes output of round function F and squeezes them into 60-bits.

$$(y_0, y_1, \dots, y_{11}) \xrightarrow{F'} (F'_0(y_0), F'_1(y_1), \dots, F'_{11}(y_{11})).$$

- $M : GF(2)^{60} \rightarrow GF(2)^{60}$ is an invertible linear transformation represented by a binary matrix M whose 5-bit columns are M_0, M_1, \dots, M_{11} .

$$M = (M_0 M_1 \dots M_{11}),$$

where M_j are 60×5 submatrices for $j = 0, 1, \dots, 11$.

- $H^* : GF(2)^{60} \rightarrow GF(2)^{60}$ is composed of fifteen 4-bit bijections.

The component functions F' , G , M , and H^* are white-box keys that cannot be exposed during the white-box implementation of encryption process.

In the white-box encryption algorithm, evaluations of T-box T are possible without knowing its component functions (white-box keys), since T is implemented as several steps of table look-ups. In fact, T-box T without final transformation H^* , say $\tilde{T}(x, y) := M(G(x) \oplus F'(y))$, can be represented by the tables of 12-bit input and 60-bit output as follows:

$$\tilde{T} : GF(2)^{60} \times GF(2)^{72} \rightarrow GF(2)^{60},$$

where its first input is $x = (x_0, x_1, \dots, x_{11})$ and the second is $y = (y_0, y_1, \dots, y_{11})$. Then we can rewrite \tilde{T} as

$$\tilde{T} : GF(2)^{11} \rightarrow GF(2)^{60},$$

$$((x_0, y_0), (x_1, y_1), \dots, (x_{11}, y_{11})) \xrightarrow{\tilde{T}} (z_0, z_1, \dots, z_{14}).$$

Define $\tilde{T}_j(x_j, y_j) = M_j(G(x_j) \oplus F'(y_j))$ for $0 \leq j \leq 11$. Then

$$\begin{aligned} \tilde{T}(x, y) &:= M(G(x) \oplus F'(y)) \\ &= M_0(G_0(x_0) \oplus F'_0(y_0)) \oplus \dots \\ &\quad \dots \oplus M_{11}(G_{11}(x_{11}) \oplus F'_{11}(y_{11})) \\ &= \tilde{T}_0(x_0, y_0) \oplus \dots \oplus \tilde{T}_{11}(x_{11}, y_{11}). \end{aligned}$$

Note that each $\tilde{T}_j(x_j, y_j)$ can be implemented as a pre-computed table with 2^{11} entries which takes 15,360 bytes. On the other hand, 60-bit output of \tilde{T} can be divided into fifteen 4-bit subblocks $(z_0, z_1, \dots, z_{14})$. Apply a 4-bit random nonlinear bijection h_k on each z_k ($k = 0, 1, \dots, 14$) in the output of lookup table $\tilde{T}_j(x_j, y_j)$. Then we have to use a cascade structure of masked adders to obtain the final output of T including H^* layer, as depicted in Chow's WB-AES.

The ciphertext of LW-WBES is produced by iterating this process 16 times with their corresponding black-box and white-box keys at each round. Note that there are no output encoding at the end of the final round, since nonlinear bijections appear in the T-box T .

C. WHITE-BOX IMPLEMENTATION AND ITS SECURITY

In order to hide white-box keys in T-box T , LW-WBES uses 12 tables $T_i : GF(2)^5 \times GF(2)^6 \rightarrow GF(2)^{60}$ for $i = 0, 1, \dots, 11$ defined as

$$T_i(x_i, k_i) := H'(\tilde{T}_i(x_i, k_i)),$$

where H' consists of 4-bit random bijections $(h'_0, h'_1, \dots, h'_{14})$ so that each output can be written as

$$T_i(x_i, k_i) = (h'_0(z_0), h'_1(z_1), \dots, h'_{14}(z_{14})).$$

Masked Adder generates The final output: $h^* \dots$

- Design rationale
- specification of WB encryption scheme
- Security claim

IV. STRUCTURAL ANALYSIS OF $S^{(1)}AS^{(2)}$

- Intro. to structural analysis
- brief history
- Our result

V. CRYPTANALYSIS OF SHI'S ALGORITHM

- round inversion
- Attack algorithm of plaintext recovery attack
- Experimental results
- Possible countermeasures

VI. CONCLUSION

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

ACKNOWLEDGMENT

The preferred spelling of the word “acknowledgment” in American English is without an “e” after the “g.” Use the singular heading even if you have many acknowledgments. Avoid expressions such as “One of us (S.B.A.) would like to thank” Instead, write “F. A. Author thanks” In most cases, sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page, not here.

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