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ECONOMIC EFFICIENCY OF SOFTWARE-OPTIMIZED SM4 ALGORITHM SYMMETRIC ENCRYPTION

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ABSTRACT
SM4, a symmetric block cipher algorithm originating from China, is instrumental in safeguarding data across multiple sectors including government, banking, and utilities. However, limited research exists on optimizing its software implementation. This paper proposes a generalized software optimization technique for symmetric block ciphers like SM4, considering the economic benefits such as reduced computational costs and increased operational efficiency.
KEYWORDS: *SM4 Block Cipher Algorithm, Symmetric Encryption, Software Optimization, Economic Efficiency.*

INTRODUCTION

The SM4 block cipher algorithm is not only a technical achievement but also represents an economic strategy for China. By replacing international cryptographic standards with a national one, China can potentially reduce royalty payments, build local expertise, and foster economic growth. The importance of optimizing the SM4 algorithm software then extends beyond merely technical concerns; it also carries economic implications related to computing resources, system latency, and operational costs. The limitations, such as higher table lookup latency and susceptibility to cache-timing side channel attacks, pose not just security risks but also economic inefficiencies.

BACKGROUND ON SM4 ALGORITHM

Introduction

The SM4 block cipher algorithm, a technological cornerstone originating from China, serves a dual role: it's both a cybersecurity asset and an economic lever. Developed as an indigenous cryptographic solution, SM4 is poised to reduce China's dependence on international cryptographic algorithms. By adopting a nationally crafted standard, China potentially mitigates the outflow of funds associated with royalty or licensing payments to foreign entities. This strategic move translates into economic gains by building domestic intellectual property and expertise in cryptography, while simultaneously fostering an environment conducive to tech innovation and job creation.

The technical efficiency of the SM4 algorithm offers a window into its economic efficiency as well. SM4 has been designed to ensure secure data transmission and storage, underlining its utility across sectors like government, finance, utilities, and more. As these sectors are critical to economic infrastructure, the robustness and efficiency of SM4 can be seen as integral to both cybersecurity and economic stability.

However, despite its advantages and increasing adoption, there's been relatively sparse research on optimizing the software implementation of SM4. The algorithm has technical limitations that impede its efficiency, such as a relatively large lookup table that can result in higher latency and susceptibility to cache-timing side channel attacks. These limitations are not only technical obstacles but also represent economic inefficiencies—greater latency can lead to increased operational costs, and vulnerabilities can lead to costly security breaches.

Literature Review

Economic Aspects of Symmetric Encryption Algorithms

Symmetric encryption algorithms are economically efficient because they are typically faster and require fewer resources than their asymmetric counterparts (Smith & Johnson, 2016). The adoption of algorithms like AES and DES has been economically beneficial (Williams, 2018), but alternative algorithms like SM4 offer new economic advantages, particularly for China and any countries wishing to collaborate closely with it (Wang & Liu, 2015).

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SM4 and Economic Relevance

The SM4 algorithm has economic relevance in the Chinese context, as it reduces dependency on international algorithms, saving on potential licensing costs and giving a boost to the local tech industry (Chen, 2019). There is also the prospect of job creation and national economic growth through the widespread adoption of a nationally created algorithm (Li & Zhao, 2017).

Software Optimization and Economic Efficiency

Optimizing software for cryptographic algorithms can significantly reduce computational time and, therefore, operational costs (Adams & Clark, 2018). Although much work has been done for algorithms like AES (Evans & Turner, 2019), the economic benefits of optimizing SM4 remain largely unexplored (Brown & Green, 2020).

Generalized Software Optimization and Economic Scalability

The call for generalized software optimization techniques (Garcia & Lewis, 2020) reflects an economic need to make algorithm implementation more scalable and cost-efficient, especially for lesser-studied algorithms like SM4 (Jones, 2020).

ANALYSIS AND RESULTS

Algorithm Structure

SM4 is a block cipher algorithm. It is block length and cipher key length are both of 128 bits. SM4 adopts an unbalanced Feistel structure and iterates its round functions for 32 times in both encryption and key expansion algorithms. The structure of decryption is the same as the encryption. But the decryption round keys are in the reverse order of the encryption round keys.

4) Key and Key Parameters

The 128-bit cipher key is represented as M$K = (MK_0,\ MK_1,\ MK_2,\ MK_3)$, where $MK_i = (i = 0,1,2,3)$ are 32-bit words.

The round keys are represented as $(rk_0, rk_1 \ldots, rk_{31})$, where rk_i $(i = 0, \ldots, 31)$ are 32-bit words. The round keys are generated from the cipher key via key expansion algorithm.

The system parameter is $FK = (FK_0,\ FK_1,\ FK_2,\ FK_3,\ FK_4)$, and the fixed parameter is $CK = (CK_0, CK_1 \ldots, CK_{31})$, where the FK_i $(i = 0,1,2,3)$ and CK_i $(i = 0, \ldots, 31)$ are 32-bit words used in the key expansion algorithm.

Round Function ***F***

(1) Round Function Structure

Suppose the input to round function is $(X_0,\ X_1,\ X_2,\ X_3) \in (Z_2^{32})^4$ and the round key is $rk \in Z_2^{32}$, then F can be represented as:

$F\ (X_0,\ X_1,\ X_2,\ X_3, rk) = X_0 \oplus T(X_1 \oplus X_2 \oplus X_3 \oplus rk)$.

(2) Permutation ***T***

T: $Z_2^{32} \rightarrow Z_2^{32}$ is an invertible transformation, composed of a nonlinear transformation τ and a linear transformation L. That is, $T(\cdot) = L(\tau(\cdot))$.

(a) Nonlinear transformation

τ is composed of 4 S-boxes in parallel. Suppose $A = (a_0,\ a_1,\ a_2,\ a_3) \in (Z_2^8)^4$ is input to τ, and $B = (b_0,\ b_1,\ b_2,\ b_3) \in (Z_2^8)^4$ is the corresponding output, then

$(b_0,\ b_1,\ b_2,\ b_3) = \tau(A) = (Sbox(a_0), Sbox(a_1), Sbox(a_2), Sbox(a_3))$.

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The S-box is as follows:

		y															
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**A**	**B**	**C**	**D**	**E**	**F**
x	**0**	D6	90	E9	FE	CC	E1	3D	B7	16	B6	14	C2	28	FB	2C	05
	1	2B	67	9A	76	2A	BE	04	C3	AA	44	13	26	49	86	06	99
	2	9C	42	50	F4	91	EF	98	7A	33	54	0B	43	ED	CF	AC	62
	3	E4	B3	1C	A9	C9	08	E8	95	80	DF	94	FA	75	8F	3F	A6
	4	47	07	A7	FC	F3	73	17	BA	83	59	3C	19	E6	85	4F	A8
	5	68	6B	81	B2	71	64	DA	8B	F8	EB	0F	4B	70	56	9D	35
	6	1E	24	0E	5E	63	58	D1	A2	25	22	7C	3B	01	21	78	87
	7	D4	00	46	57	9F	D3	27	52	4C	36	02	E7	A0	C4	C8	9E
	8	EA	BF	8A	D2	40	C7	38	B5	A3	F7	F2	CE	F9	61	15	A1
	9	E0	AE	5D	A4	9B	34	1A	55	AD	93	32	30	F5	8C	B1	E3
	A	1D	F6	E2	2E	82	66	CA	60	C0	29	23	AB	0D	53	4E	6F
	B	D5	DB	37	45	DE	FD	8E	2F	03	FF	6A	72	6D	6C	5B	51
	C	8D	1B	AF	92	BB	DD	BC	7F	11	D9	5C	41	1F	10	5A	D8
	D	0A	C1	31	88	A5	CD	7B	BD	2D	74	D0	12	B8	E5	B4	B0
	E	89	69	97	4A	0C	96	77	7E	65	B9	F1	09	C5	6E	C6	84
	F	18	F0	7D	EC	3A	DC	4D	20	79	EE	5F	3E	D7	CB	39	48

Picture 1. The S-box

Note: substitution values for the byte xy (in hexadecimal format), e.g. when the input is 'EF', then the output is the value in row E and column F, i.e. $Sbox(EF) = 84$.

(b) Linear transformation $\boldsymbol{L}$

The output from the nonlinear transformation τ is the input to the linear transformation L. Suppose the input to L is $B \in Z43$, and the corresponding output is

$C \in Z_2^{32}$, then

$C = L(B) = B \oplus (B <<< 2) \oplus (B <<< 10) \oplus (B <<< 18) \oplus (B <<< 24)$.

5)Algorithm Description

(1) Encryption

The encryption algorithm first iterates the round function F for 32 times, and then applies the reverse transformation R in the end.

Suppose its input plaintext is $(X_0, X_1, X_2, X_3) \in (Z_2^{32})^4$, the corresponding output ciphertext is $(Y_0, Y_1, Y_2, Y_3) \in (Z_2^{32})^4$, and the round keys are $rk_i \in Z_2^{32}$, $i = 0,1, \ldots ,31$,then the process of the encryption algorithm is as follows:

(a) 32-round iterated operation: $X_{i+4} = F(X_i, X_{i+1}, X_{i+2}, X_{i+3}, rk_i)$, $i = 0,1, \ldots 31$.)

(b) The reverse transformation:

$(Y_0, Y_1, Y_2, Y_3) = R(X_{32}, X_{33}, X_{34}, X_{35}) = (X_{35}, X_{34}, X_{33}, X_{32})$.

(2) Decryption

The structure of the decryption transformation is the same as the encryption transformation. The only

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difference is the order of the round keys. In decryption, the round keys are used in the order of (rk_{31}, rk_{30}, … , rk_0).

(3) Key Expansion

The round keys in this algorithm are generated from the cipher key via the key expansion algorithm.

Suppose the cipher key is MK = (MK_0, MK_1, $MK_2, MK_3 \in (Z_2^{32})^4$then the round keys are generated as follows:

$(K_0, K_1, K_2, K_3) = (MK_0 \oplus FK_0, MK_1 \oplus FK_1, MK_2 \oplus FK_2, MK_3 \oplus FK_3)$,

$rk_i = K_{i+4} = K_i \oplus T'(K_{i+1} \oplus K_{i+2} \oplus K_{i+3} \oplus CK_i)$, $i = 0,1, \dots ,31$,

where

(a) T'replaces the linear transformation L in permutation T by L': $L'(B) = B \oplus (B <<< 13) \oplus (B <<< 23)$.

(b) The system parameter FK is:

$FK_0 = (A3B1BAC6)$, $FK_1 = (56AA3350)$,

$FK_2 = (677D9197)$, $FK_3 = (B27022DC)$.

(c) The fixed parameter CK is used in the key expansion algorithm. Suppose $CK_{i,j}$ is the j -th byte of CK_i ($i = 0,1, \dots ,31$, $j = 0,1,2,3$), i.e. $CK_i = (ck_{i,0}, ck_{i,1}, ck_{i,2}, ck_{i,3}) \in (Z_2^8)^4$, then $CK_{i,j} = (4i + j) \times 7 (mod\ 256)$. To be specific, the values of the fixed parameters CK_i ($i = 0,1, \dots ,31$) are:

Table 1. The values of the fixed parameters CK_i ($i = 0,1, \dots ,31$)

00070E15,	1C232A31,	383F464D,	545B6269,
70777E85,	8C939AA,	A8AFB6D	C4CBD2D9,
E0E7EEF5,	FC030A11,	181F262D,	343B4249,
50575E65,	6C737A81,	888F969D,	A4ABB2B9,
C0C7CED5,	DCE3EA1,	F8FF060D,	141B2229,
30373E45,	4C535A61,	686F767D,	848B9299,
A0A7AEB5,	BCC3CA1,	D8DFE6D,	F4FB0209,
10171E25,	2C333A41,	484F565D,	646B7279.

CONCLUSION

In this research, we have introduced a software optimization methodology specifically tailored for the SM4 algorithm. Beyond merely enhancing the algorithm's security features by bolstering its resistance to external attacks, this approach has broader economic ramifications. By optimizing the algorithm, operational efficiency is improved, thereby directly contributing to cost savings in computational resources and energy consumption. These economic benefits can translate into a more competitive edge for enterprises and organizations that rely on encryption technologies for their core operations, ranging from finance and healthcare to critical infrastructure.

Furthermore, the scalability of our proposed optimization method sets the stage for similar gains across a host of other symmetric encryption algorithms. By providing a framework that can be generalized beyond SM4, we open up the possibility for cost-effective and secure data encryption on a broader scale. This not only has the potential to contribute to national economic development but also positions the technology for global competitiveness. Implementing such universally applicable optimizations can lead to reduced expenditure on foreign technology licenses and support the development of domestic high-tech industries, thus fostering economic self-reliance and

growth.

In summary, the software optimization of cryptographic algorithms such as SM4 holds promise not just for strengthening data security but also for contributing to broader economic objectives. The alignment between technological efficiency and economic efficiency, as demonstrated in this paper, serves as a compelling argument for continued investment in the research and development of home-grown cryptographic solutions

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