CLOC: Authenticated Encryption for Short Input

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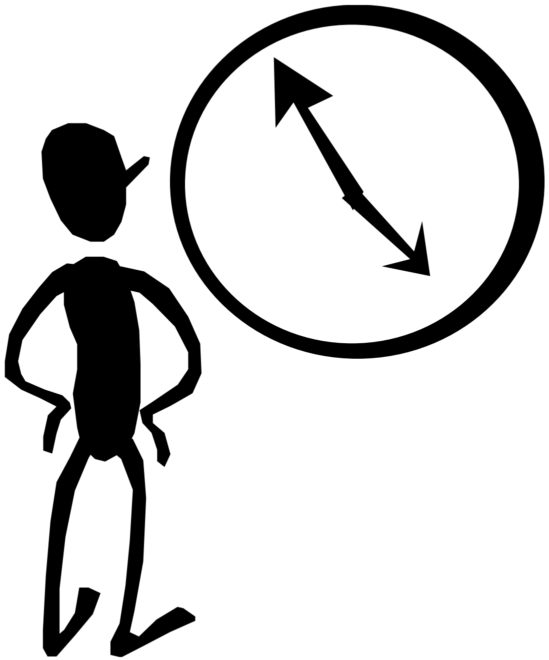
Outline

- A new authenticated encryption with associate data scheme (AEAD)
- CLOC: Compact Low-Overhead CFB, pronounced as “clock”



CLOC Design Goal

- Provably secure AEAD that is based on a blockcipher
  - Standard security notions for privacy and authenticity
- To improve previous schemes, CCM, EAX, and EAX-prime
  - the implementation overhead beyond the blockcipher
  - the precomputation complexity
  - the memory requirement

CLOC Design Goal

- Suitable for handling short input data, say 16 bytes, without needing precomputation nor large memory
- Suitable for small microprocessors, where the word size is typically 8 bits or 16 bits, and there are significant restrictions in the size and the number of registers

CCM, EAX, and EAX-Prime

- AEADs based on a blockcipher
- CCM (NIST SP 800-38C)
  - not online
- EAX (ISO/IEC 19772)
  - precomputation costs ($L = E_K(0)$, 2L, 4L, $E_K(1)$, and $E_K(2)$)
  - time and memory
- EAX-prime (ANSI C12.22)
  - efficiently handles short input data with small memory
  - practical attacks
- CLOC removes these limitations
  - remove $L = E_K(0)$ or doubling operations over $GF(2^n)$

Short Input Data

- Performance for short input data matters:
  - Low-power sensor networks
    - Zigbee: at most 127 bytes
  - Bluetooth Low Energy: at most 47 bytes
  - Electronic Product Code (EPC): typically 96 bits
- For long input data, the efficiency of CLOC is the same as CCM, EAX, and EAX-prime
  - 2 blockcipher calls per 1 plaintext block
  - CLOC is for short input data

CLOC Properties

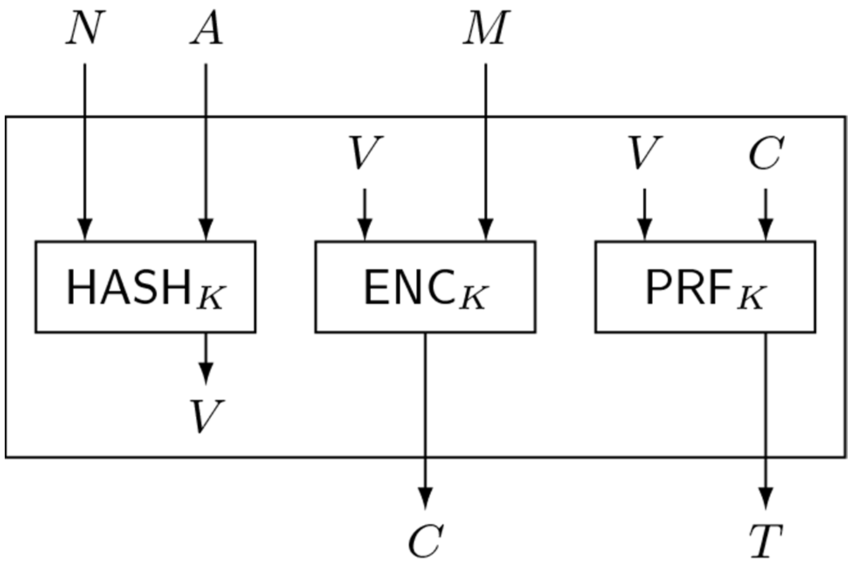
- Nonce-based AEAD
- uses only the encryption of the blockcipher both for encryption and decryption
- When $|A| \geq 1$, it makes $|N|_n + |A|_n + 2|M|_n$ blockcipher calls for a nonce N, associated data A, and a plaintext M
  - where $|X|$ is the length of X in bits and $|X|_n$ is the length in n-bit blocks
  - $1 \leq |N| \leq n-1$, so $|N|_n = 1$
  - No precomputation (blockcipher calls, generation of key dependent tables, . . .) is needed
  - when $|A| = 0$, it needs $|N|_n + 1 + 2|M|_n$ calls

CLOC Properties

- For short input data
  - 1-block nonce, 1-block associated data, and 1-block plaintext
  - CLOC: 4 calls
  - CCM: 5 or 6 calls
  - EAX: 7 calls (where 3 out of 7 can be precomputed)
  - EAX-prime: 5 calls (where 1 out of 5 can be precomputed)
- Static associated data can be handled efficiently
- It works with two state blocks (i.e. 2n bits)
- Sequential

Overview of the Scheme

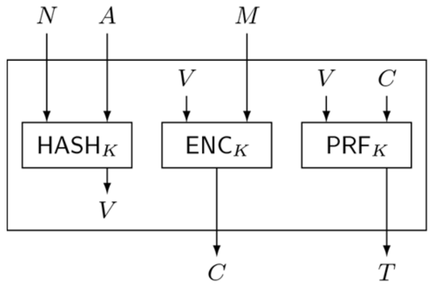
- Encrypt-then-PRF paradigm
- uses a variant of CFB mode in its encryption part and a variant of CBC MAC in the authentication part



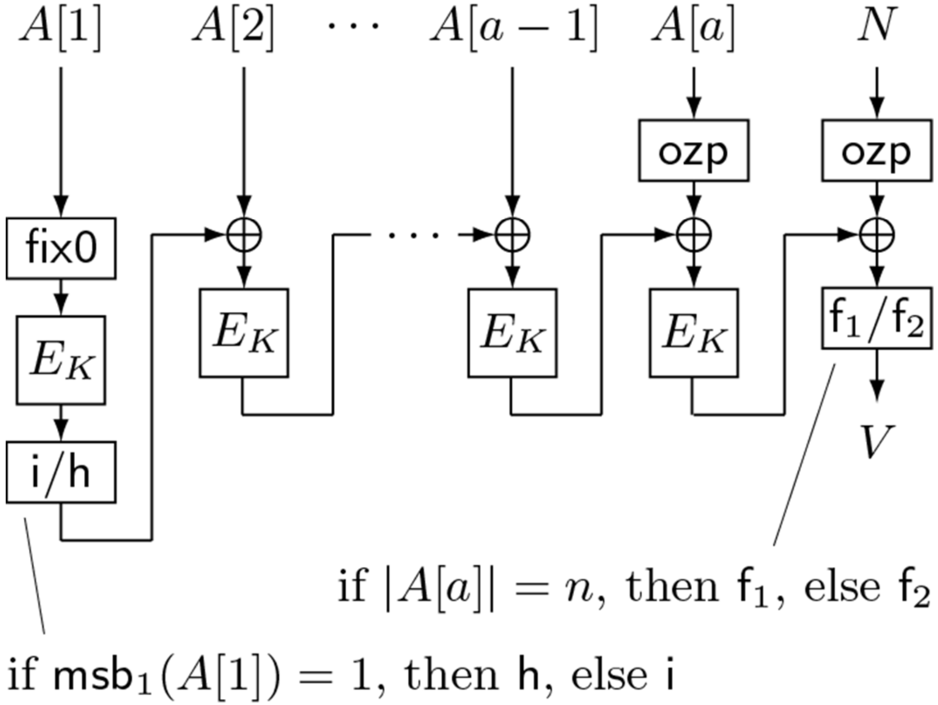
Tools

- The one-zero padding function: ozp
  - ozp(X) = X if |X|=jn for some j > 0, and ozp(X) = X||10…0
- The tweak functions: f_1, f_2, g_1, g_2, and h
  - use them to directly update the state
- The bit fixing functions: fix0 and fix1
  - fix0(X): overwrite msb_1(X) with 0
  - fix1(X): overwrite msb_1(X) with 1
    - fix1(0000) = 1000, fix1(1100) = 1100

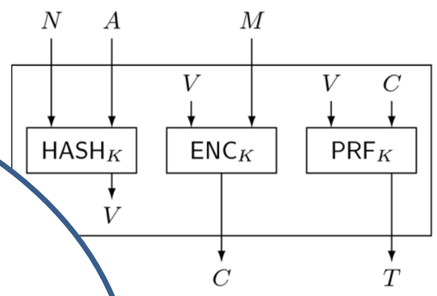
V <- $HASH_K$(A,N)



- A variant of CBC MAC
- $1 \leq |N| \leq n-1$



V <- $\text{HASH}_K(A,N)$



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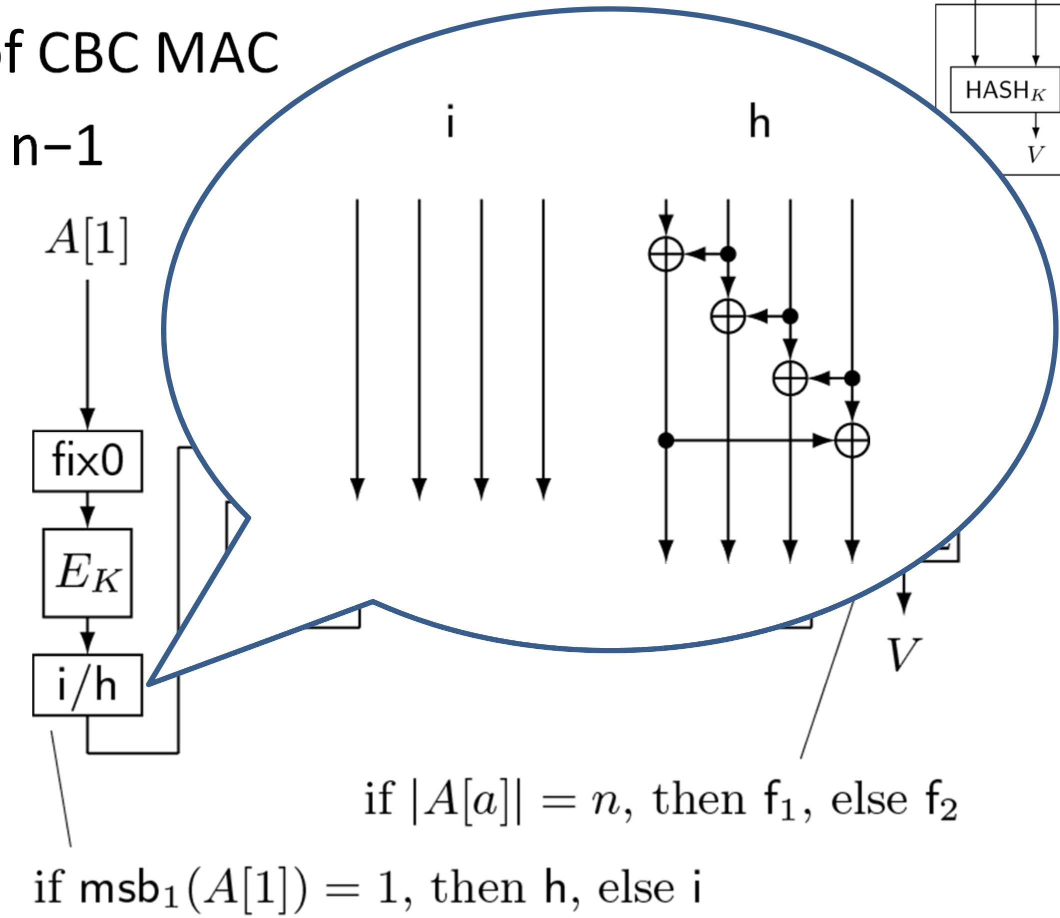

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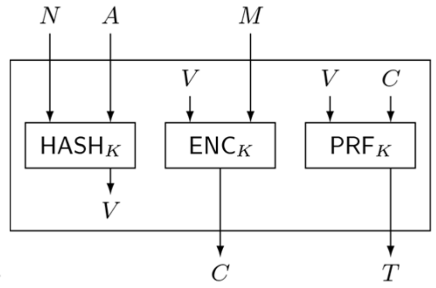
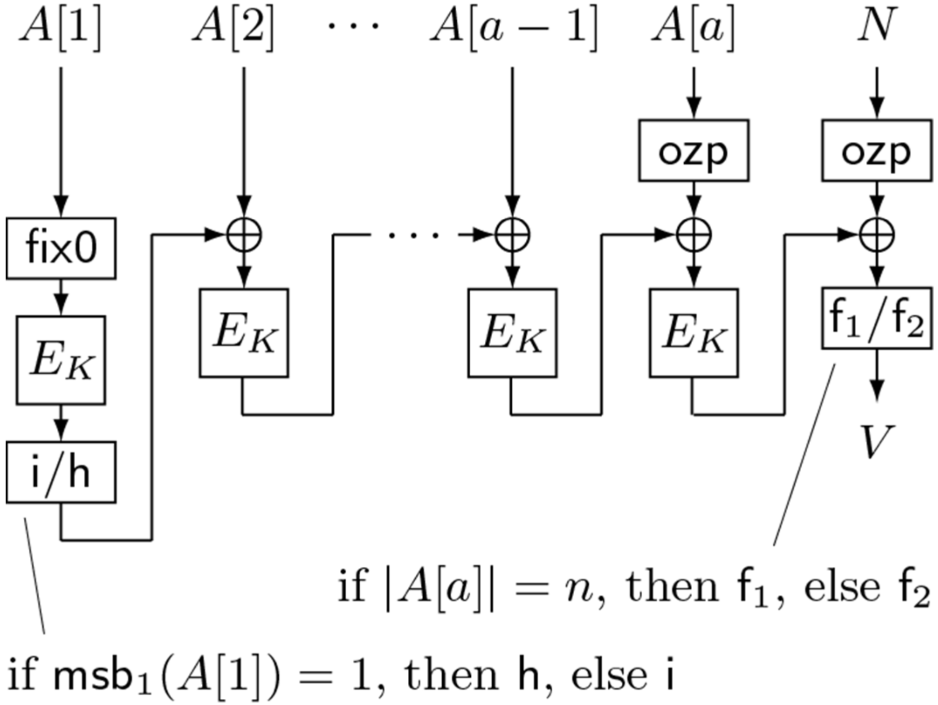
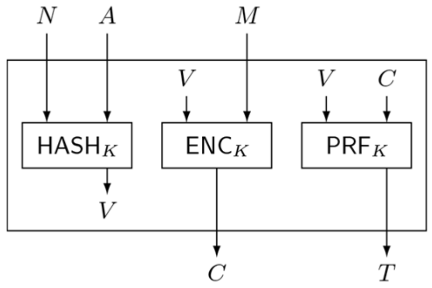
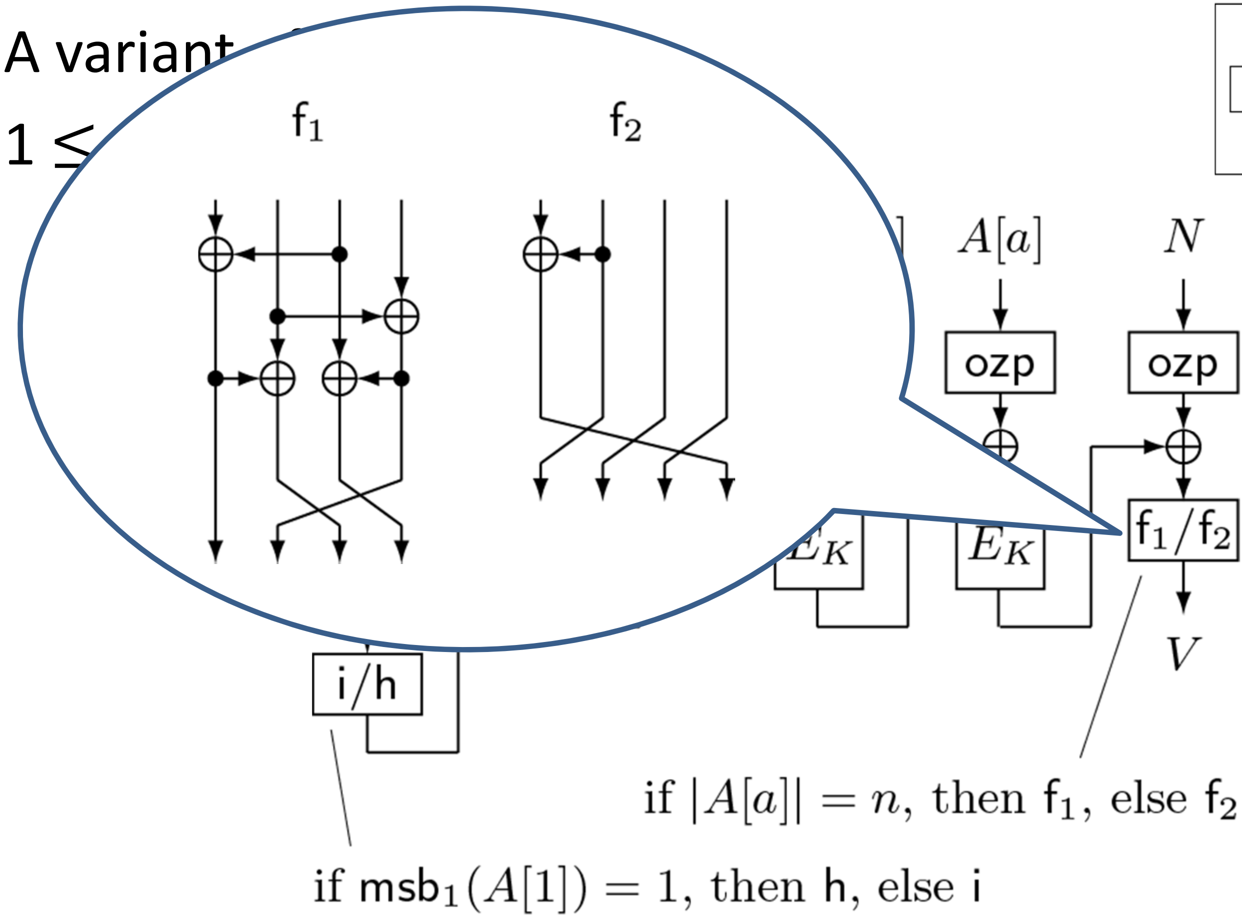




V <- HASH$_K$(A,N)

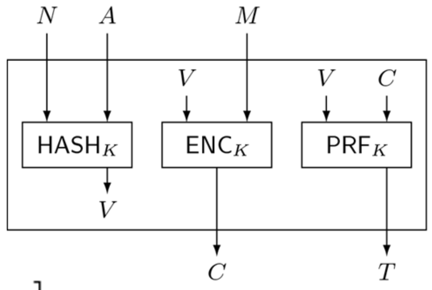
- A variant
- 1 ≤

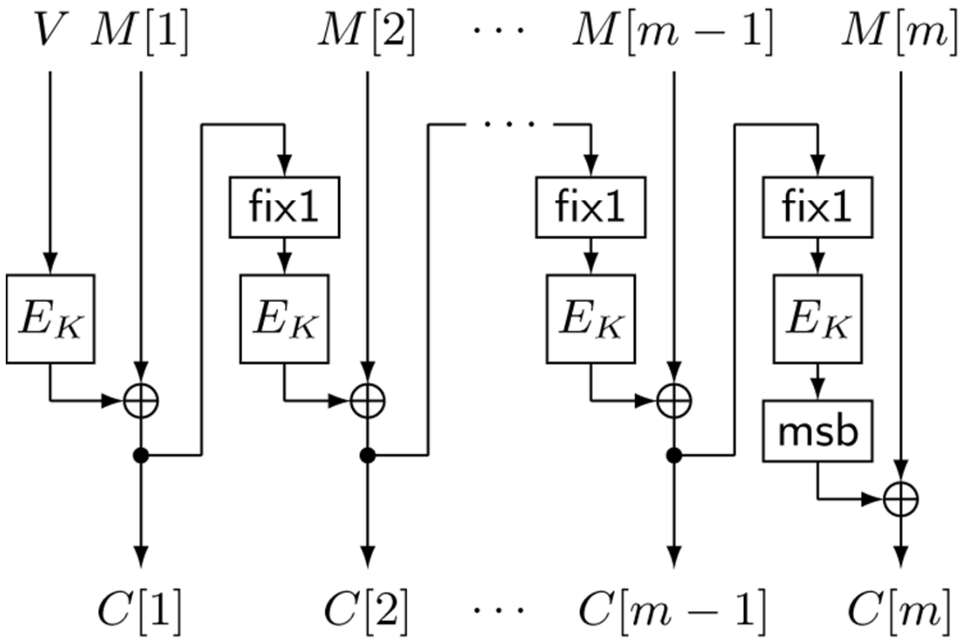




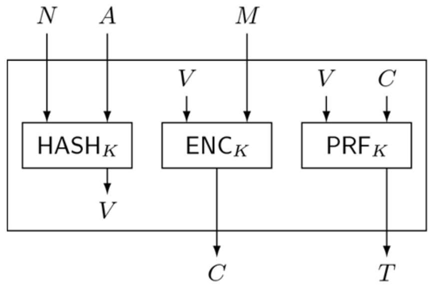
C <- ENC$_K$(V,M)

- A variant of CFB mode

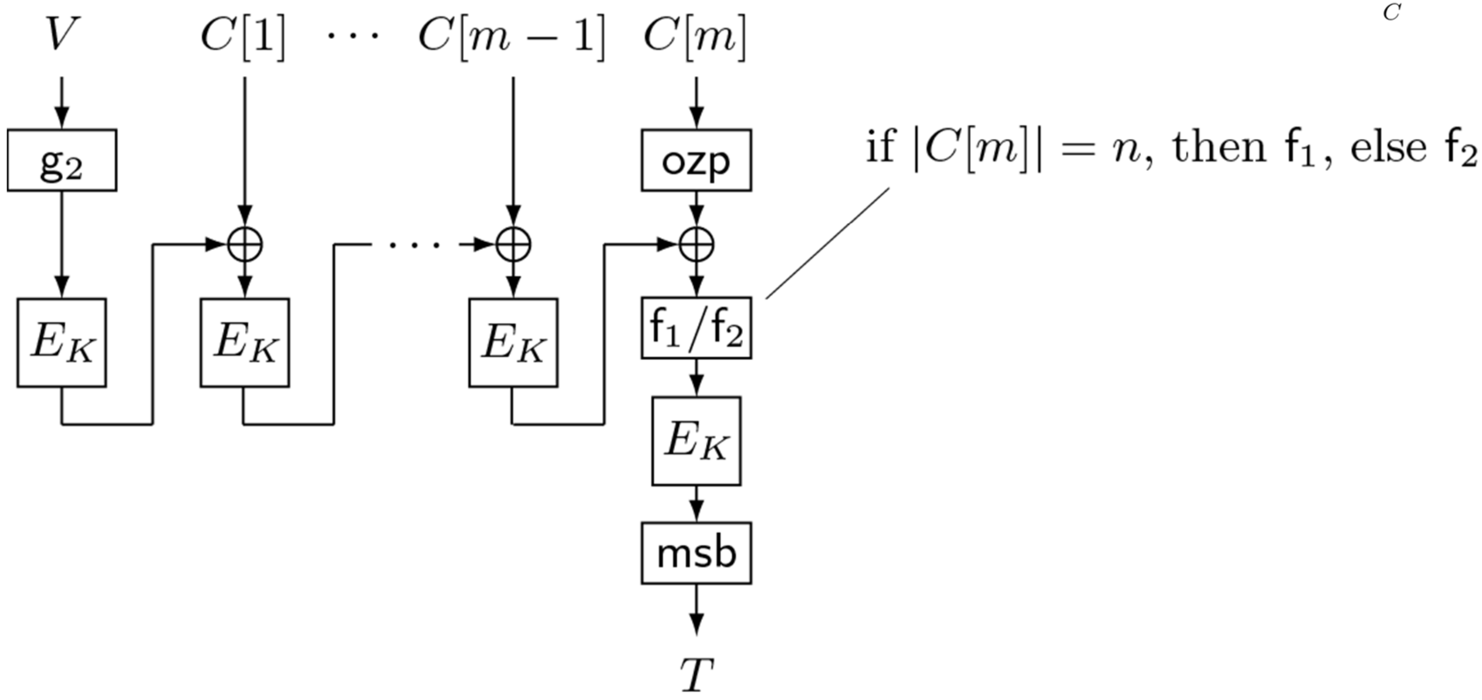




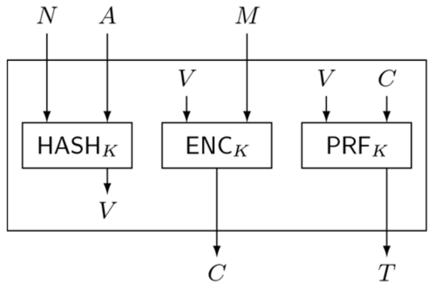
T <- $PRF_K(V,C)$



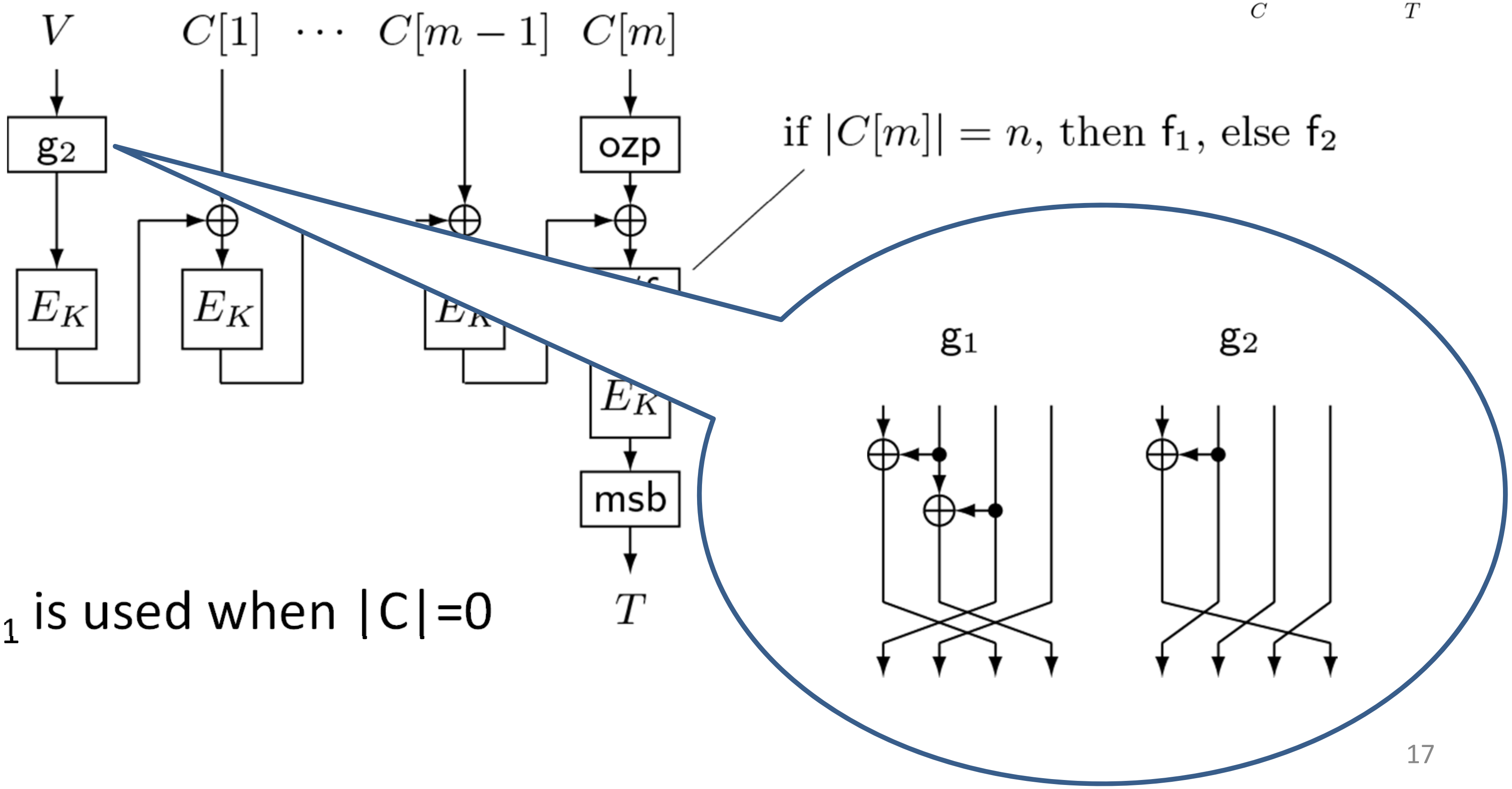
- A variant of CBC MAC



T <- $\text{PRF}_K(V,C)$



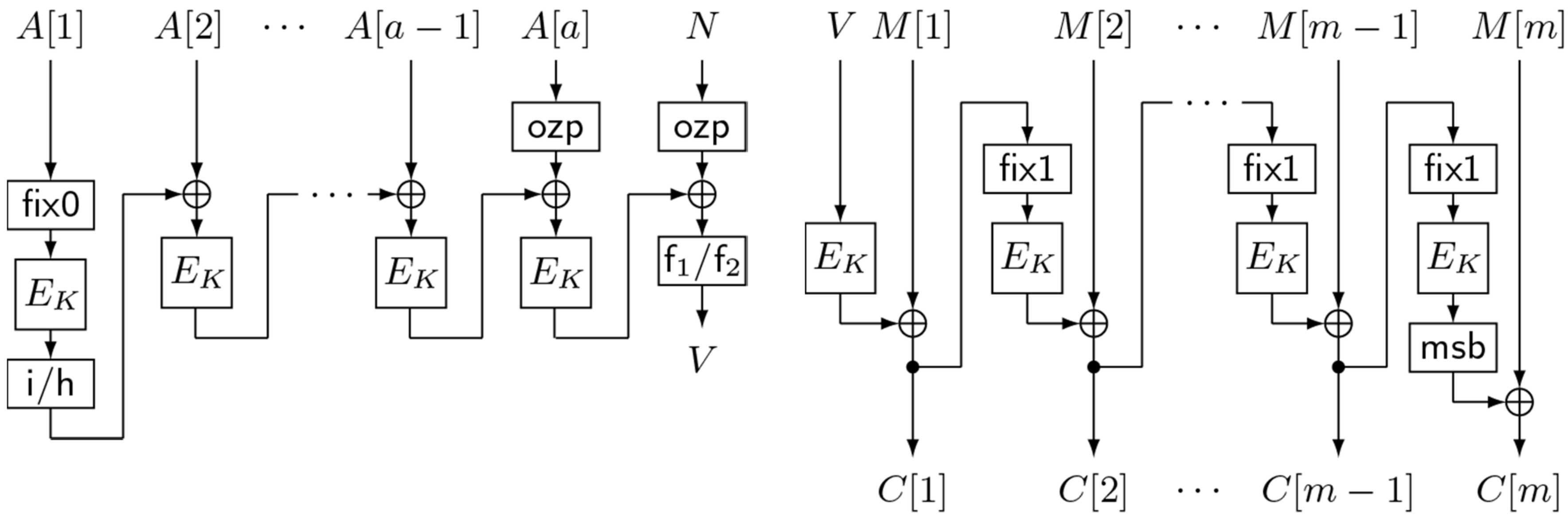
- A variant of CBC MAC



- g_1 is used when $|C|=0$

Rationale

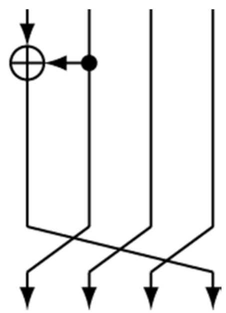
- The bit fixing functions
  - used to logically separate CBC MAC and CFB mode
  - otherwise, attacks are possible



Rationale

- The tweak functions
  - There are 55 differential probability constraints
    - K xor $f_1(K)$, $f_1(K)$ xor $g_1(f_1(h(K)))$, . . .
  - Define a matrix M as

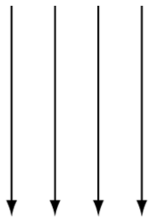
$$\mathbf{M} = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$



  - K · M = (K[1], K[2], K[3], K[4]) · M
    = (K[2], K[3], K[4], K[1] xor K[2])

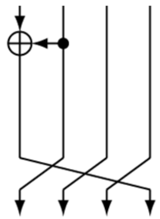
$\mathbf{M}^0$

$$\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}$$



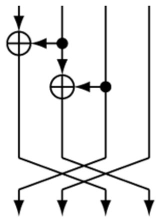
$\mathbf{M}^1$

$$\begin{pmatrix}0&0&0&1\\1&0&0&1\\0&1&0&0\\0&0&1&0\end{pmatrix}$$



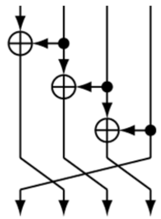
$\mathbf{M}^2$

$$\begin{pmatrix}0&0&1&0\\0&0&1&1\\1&0&0&1\\0&1&0&0\end{pmatrix}$$



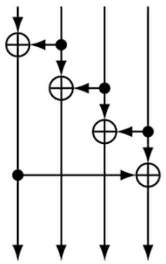
$\mathbf{M}^3$

$$\begin{pmatrix}0&1&0&0\\0&1&1&0\\0&0&1&1\\1&0&0&1\end{pmatrix}$$



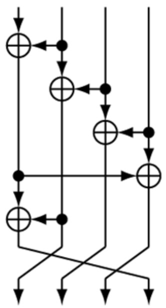
$\mathbf{M}^4$

$$\begin{pmatrix}1&0&0&1\\1&1&0&1\\0&1&1&0\\0&0&1&1\end{pmatrix}$$



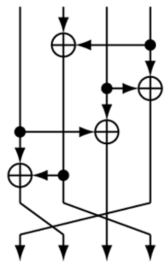
$\mathbf{M}^5$

$$\begin{pmatrix}0&0&1&1\\1&0&1&0\\1&1&0&1\\0&1&1&0\end{pmatrix}$$



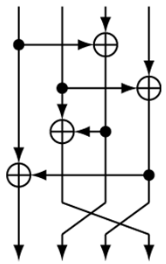
$\mathbf{M}^6$

$$\begin{pmatrix}0&1&1&0\\0&1&0&1\\1&0&1&0\\1&1&0&1\end{pmatrix}$$



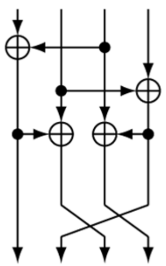
$\mathbf{M}^7$

$$\begin{pmatrix}1&1&0&1\\1&0&1&1\\0&1&0&1\\1&0&1&0\end{pmatrix}$$



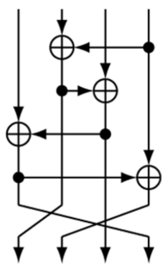
$\mathbf{M}^8$

$$\begin{pmatrix}1&0&1&0\\0&1&1&1\\1&0&1&1\\0&1&0&1\end{pmatrix}$$



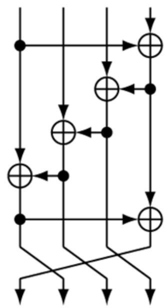
$\mathbf{M}^9$

$$\begin{pmatrix}0&1&0&1\\1&1&1&1\\0&1&1&1\\1&0&1&1\end{pmatrix}$$



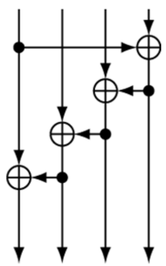
$\mathbf{M}^{10}$

$$\begin{pmatrix}1&0&1&1\\1&1&1&0\\1&1&1&1\\0&1&1&1\end{pmatrix}$$



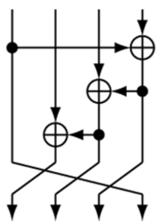
$\mathbf{M}^{11}$

$$\begin{pmatrix}0&1&1&1\\1&1&0&0\\1&1&1&0\\1&1&1&1\end{pmatrix}$$



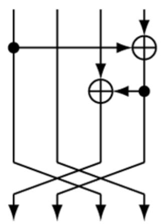
$\mathbf{M}^{12}$

$$\begin{pmatrix}1&1&1&1\\1&0&0&0\\1&1&0&0\\1&1&1&0\end{pmatrix}$$



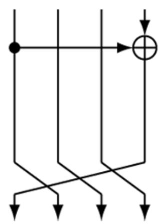
$\mathbf{M}^{13}$

$$\begin{pmatrix}1&1&1&0\\0&0&0&1\\1&0&0&0\\1&1&0&0\end{pmatrix}$$



$\mathbf{M}^{14}$

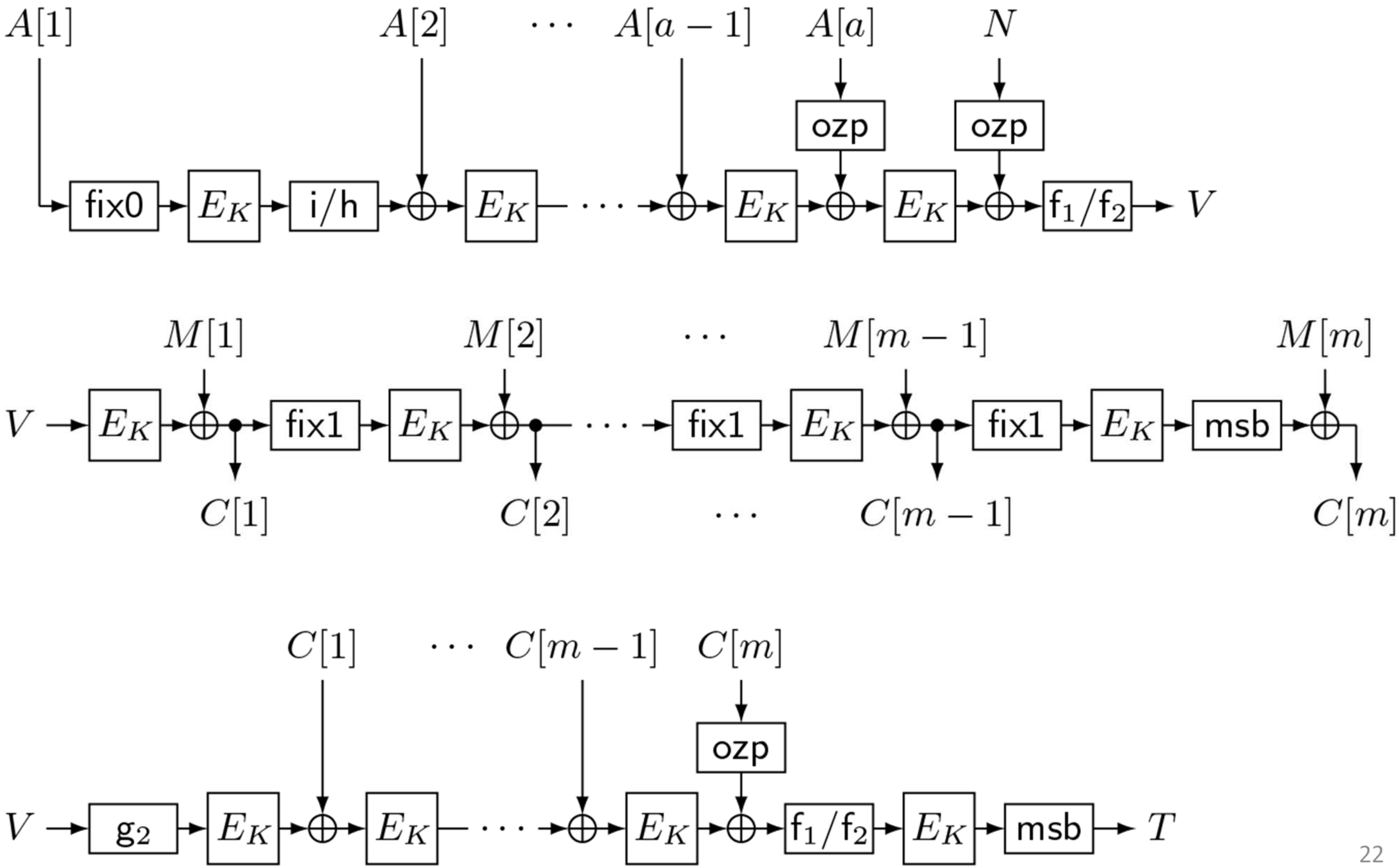
$$\begin{pmatrix}1&1&0&0\\0&0&1&0\\0&0&0&1\\1&0&0&0\end{pmatrix}$$



Rationale

- The tweak functions
  - associate $(i_1, i_2, i_3, i_4, i_5) \in \{1, . . . , 14\}^5$ with (f_1, f_2, g_1, g_2, h)
  - f_1: M^{i1}, f_2: M^{i2}, g_1: M^{i3}, g_2: M^{i4}, h: M^{i5}
- Tested all $(i_1, i_2, i_3, i_4, i_5) \in \{1, . . . , 14\}^5$
  - e.g., K xor $f_1(K)$: the rank of I xor M^{i1} is full (I is the identity matrix)
  - 14^5 -> 864 candidates
- Defined a cost function to choose the best exponentiations
  - roughly measures the computational cost of (f_1, f_2, g_1, g_2, h)
  - $(i_1, i_2, i_3, i_4, i_5) = (8, 1, 2, 1, 4)$

Works with Two State Blocks



Security

- Privacy:
  - Indistinguishability of ciphertexts from random bits against nonce-respecting adversaries in a chosen plaintext attack setting

- $\mathbf{Adv}^{\mathrm{priv}}_{\mathrm{CLOC}[E,\ell_N,\tau]}(\mathcal{A}) \stackrel{\mathrm{def}}{=} \Pr\left[\mathcal{A}^{\mathrm{CLOC}\text{-}\mathcal{E}_K(\cdot,\cdot,\cdot)} \Rightarrow 1\right] - \Pr\left[\mathcal{A}^{\$(\cdot,\cdot,\cdot)} \Rightarrow 1\right]$

- $\mathbf{Adv}^{\mathrm{priv}}_{\mathrm{CLOC}[\mathrm{Perm}(n),\ell_N,\tau]}(\mathcal{A}) \leq \dfrac{5\sigma_{\mathrm{priv}}^2}{2^n}$, where $\sigma_{\mathrm{priv}} = q + \sigma_A + 2\sigma_M$

Security

- Authenticity:
  - Unforgeability against nonce-reusing adversaries in a chosen ciphertext attack setting
  - A strong adversary

- $\mathbf{Adv}^{\text{auth}}_{\text{CLOC}[E,\ell_N,\tau]}(\mathcal{A}) \stackrel{\text{def}}{=} \Pr\left[\mathcal{A}^{\text{CLOC-}\mathcal{E}_K(\cdot,\cdot,\cdot),\text{CLOC-}\mathcal{D}_K(\cdot,\cdot,\cdot,\cdot)} \text{ forges}\right]$

- $\mathbf{Adv}^{\text{auth}}_{\text{CLOC}[\text{Perm}(n),\ell_N,\tau]}(\mathcal{A}) \leq \frac{5\sigma_{\text{auth}}^2}{2^n} + \frac{q'}{2^\tau}$

  where $\sigma_{\text{auth}} = q + \sigma_A + 2\sigma_M + q' + \sigma_{A'} + \sigma_{C'}$

Software Implementation

- Embedded software
- Atmel AVR ATmega128
  - 8-bit microprocessor
  - AES from [AVR-Crypto-Lib] written in assembler
    - 156.7 cpb for encryption, 196.8 cpb for decryption
  - CLOC, EAX, and OCB3
    - modes are written in C
    - OCB3 code from [OCB News and Code] w/ modification
      - doubling operations are on-line, large precomputation may not be suitable to handle short input data for microprocessors
  - compiled with Atmel Studio 6

Software Implementation

	ROM (bytes)	RAM (bytes)	Init (cycles)	Speed (cycles/byte)					
				Data 16	32	64	96	128	256
CLOC	2980	362	1999	750.1	549.0	448.4	414.9	398.2	373.0
EAX	2772	402	12996	913.6	632.5	490.8	443.6	419.9	384.5
OCB-E	5010	971	4956	1217.5	736.1	495.5	412.2	375.1	314.9
OCB-D	5010	971	4956	1252.2	773.4	534.0	451.2	414.3	354.4

- 1-block AD, no static AD computation
- cycle counting is obtained by the simulation of Atmel Studio 6
- RAM is measured with a public tool [EZSTACK]
- In CLOC, the RAM usage is low and Init is fast, and it is fast for short input data, up to around 128 bytes

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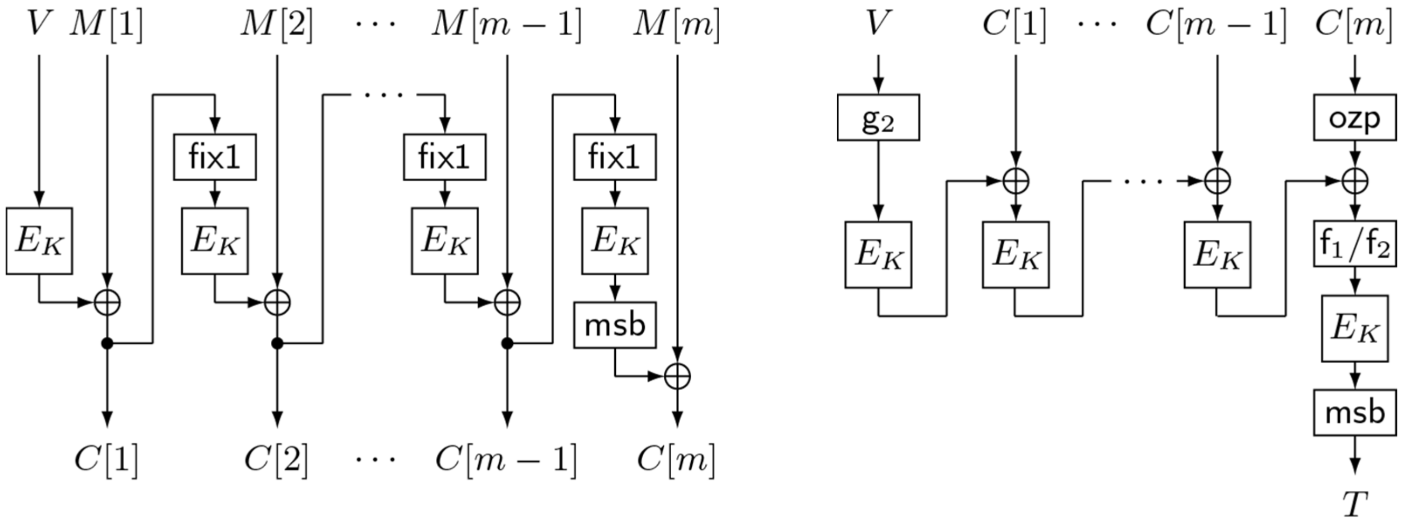
updated from the pre-proceedings

Software Implementation

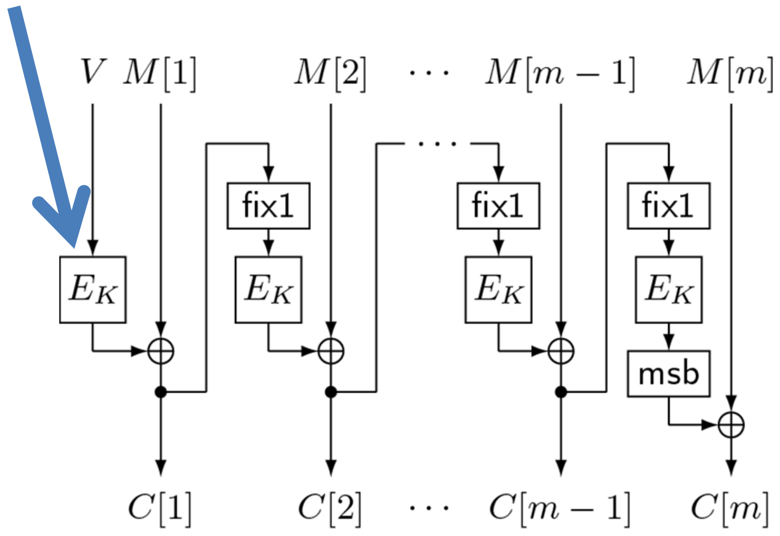
- General purpose CPU
- Intel processor, Core i5-3427U 1.80GHz (Ivy Bridge family)
- AES-128, AES-NI
- CLOC: about 4.9 cpb for long input data (more than 2^{20} blocks)
- AES calls in CFB mode and CBC MAC (in tag generation) can be done in parallel

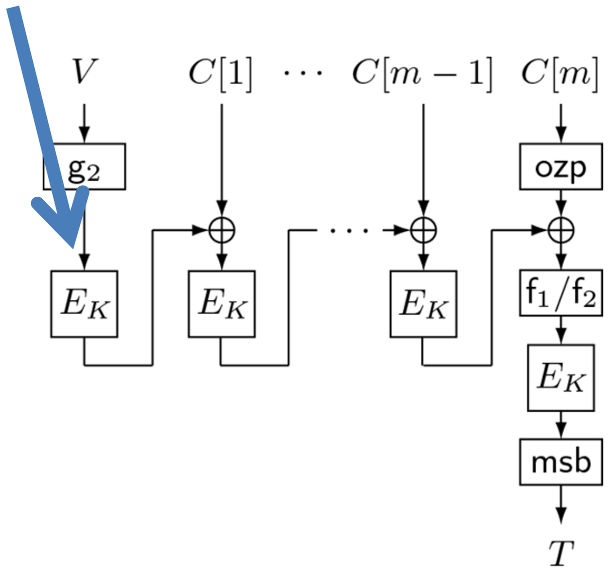
Software Implementation



- For long input data, CLOC is close to the speed of serial encryption only mode (CBC mode)
- CLOC: about 4.9 cpb
  - serial AES-128 encryption: about 4.3 cpb

Software Implementation





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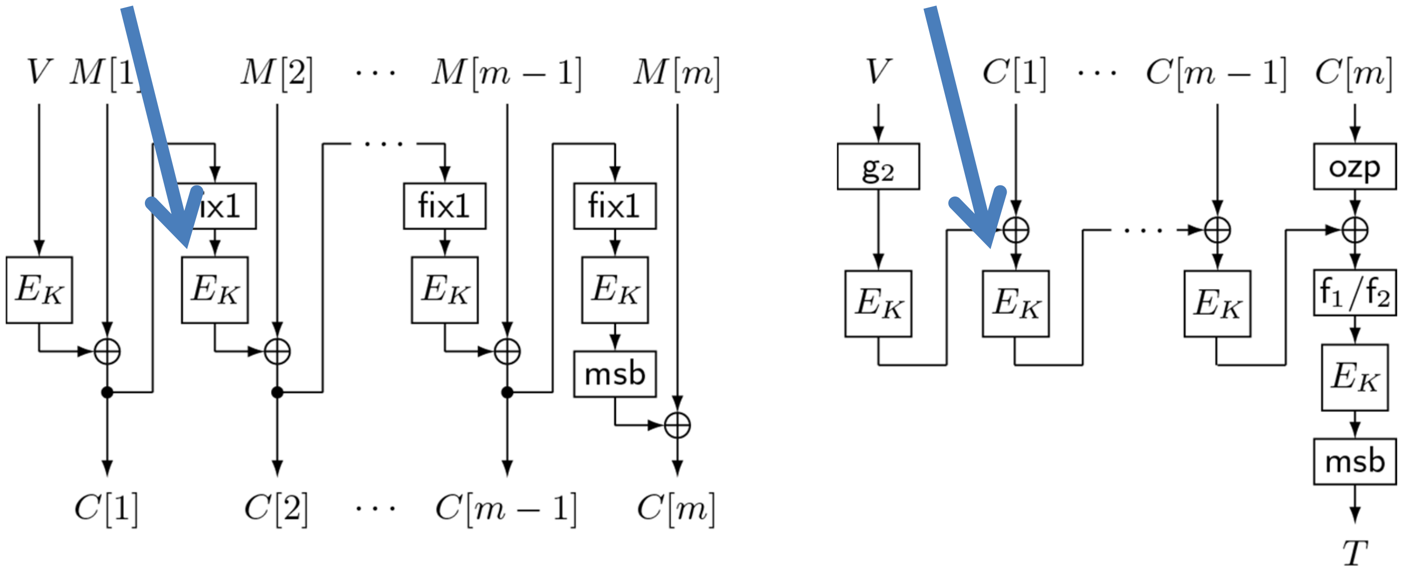

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- CLOC: about 4.9 cpb
  - serial AES-128 encryption: about 4.3 cpb

Hardware Implementation

- Not the main focus
- Altera FPGA, Cyclone IV GX (EP4CGX110DF31C7)
  - w/ AES-128, composite field S-box implementation, round-based architecture
- Size is measured in terms of LEs (logic elements)
- one block of associated data and 8 blocks of plaintexts

	Size (LE)	Max. Freq. (MHz)	Throughput (Mbit/sec)
CLOC	5628	82.1	400.7
EAX	6453	61.3	342.2
AES Enc	3175	98.7	971.7

- Slightly smaller and faster than EAX

Conclusions

- Designed CLOC and analyzed the security and the efficiency
- CLOC is designed to efficiently handle short input data and suitable for use in small microprocessors
  - it works without heavy precompuation nor large memory