Blockcipher-based Authentcated Encryption: How Small Can We Go?

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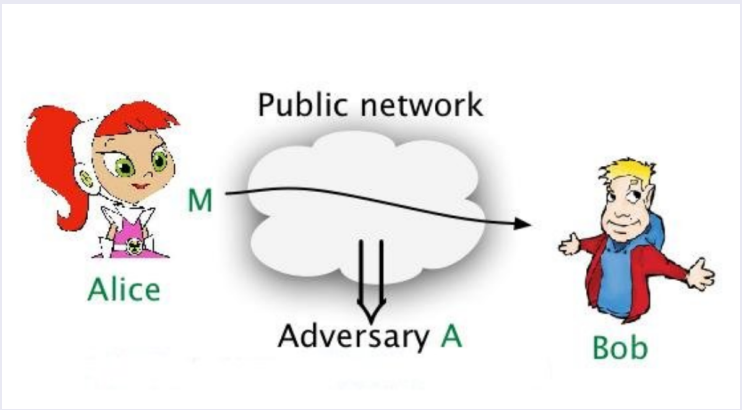
Authenticated Encryption (AE)



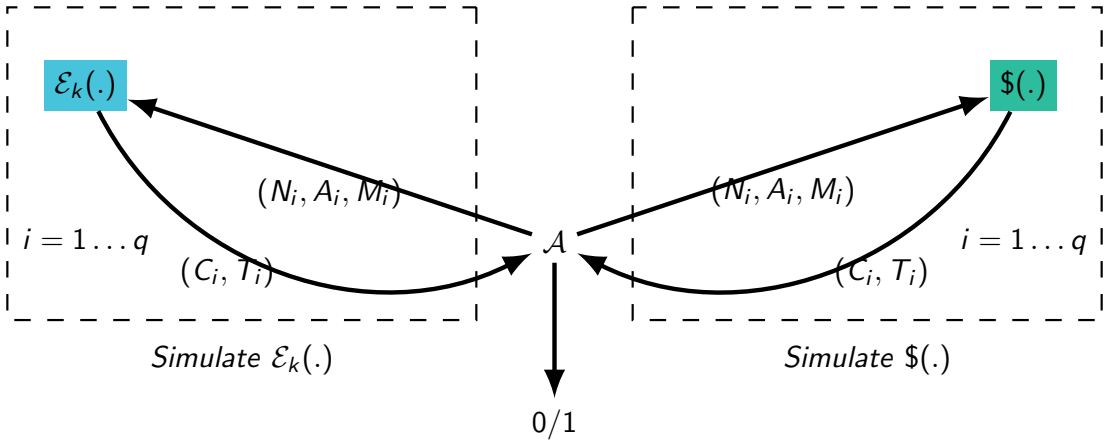
More Formally....

- AE.enc : $\mathcal{M} \times \mathcal{D} \times \mathcal{N} \times \mathcal{K} \rightarrow \mathcal{C}$
- AE.dec : $\mathcal{C} \times \mathcal{D} \times \mathcal{N} \times \mathcal{K} \rightarrow \mathcal{M} \cup \perp$

Goal	Primitive	Security
Privacy	Symmetric Encryption	IND-CPA
Integrity	MAC/Others	INT-CTXT

Table: Security Properties

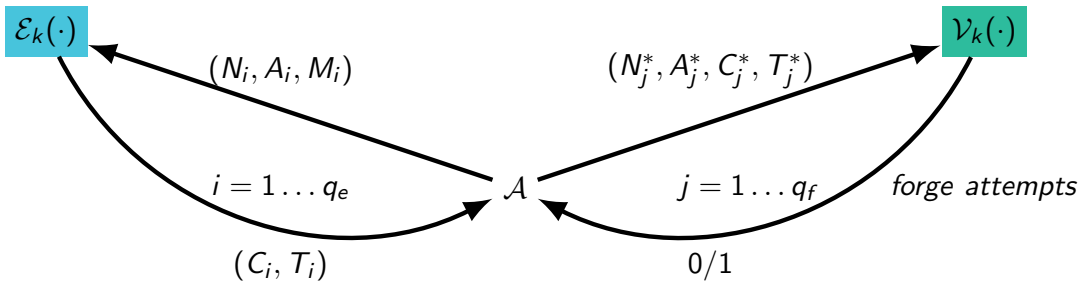
IND-CPA Security for Privacy



$$\Delta_{\mathcal{A}}(\mathcal{O}_1; \mathcal{O}_2) = |\Pr[\mathcal{A}^{\mathcal{O}_1} = 1] - \Pr[\mathcal{A}^{\mathcal{O}_2} = 1]|.$$

- $\mathbf{Adv}^{\mathrm{PRIV}}_{\mathcal{AE}}(\mathcal{A}) := \Delta_{\mathcal{A}}(\mathcal{E}_K; \$)$
- $\mathbf{Adv}^{\mathrm{PRIV}}_{\mathcal{AE}}(q, \sigma, t) = \max_{\mathcal{A}} \mathbf{Adv}^{\mathrm{PRIV}}_{\mathcal{AE}}(\mathcal{A})$
- t: Time, q: #queries , σ: # blocks in all queries

INT-CTXT Security for Integrity



- $\mathcal{A}$ *forges* if $\exists\ (N_j^*, A_j^*, C_j^*, T_j^*) \ni \mathcal{V}_k(N_j^*, A_j^*, C_j^*, T_j^*) = 1$

- $\mathbf{Adv}^{\mathrm{INT}}_{\mathcal{AE}}(\mathcal{A}) := Pr[\mathcal{A}^{\mathcal{E}_k}\ forges]$
- $\mathbf{Adv}^{\mathrm{INT}}_{\mathcal{AE}}((q_e, q_f), (\sigma_e, \sigma_f), t) = \max_{\mathcal{A}} \mathbf{Adv}^{\mathrm{INT}}_{\mathcal{AE}}(\mathcal{A})$

Current State of the Art

Structural Properties

Schemes	CLOC-SILC	AES-JAMBU	iFEED
State	2n + k	1.5n + k	3n + k
Rate	$\frac{1}{2}$	$\frac{1}{2}$	1
Proofs	Yes	Yes (integrity only)	Yes (wrong)

Here n is the blocksize of blockcipher

Main Idea and Motivation Behind the Construction

- Very *small* cipher state
- Provably Security in terms of both *Privacy* and *Integrity*

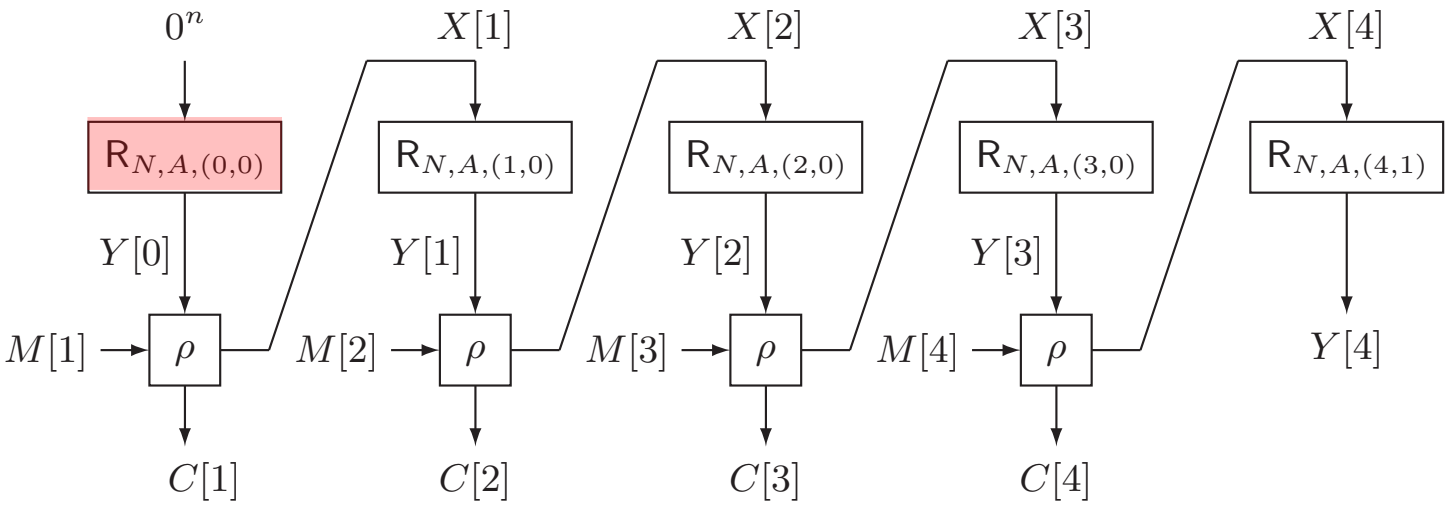
iCOFB Construction

Generic *Combined* Feedback Mode

Instantiated by *COFB* AE scheme

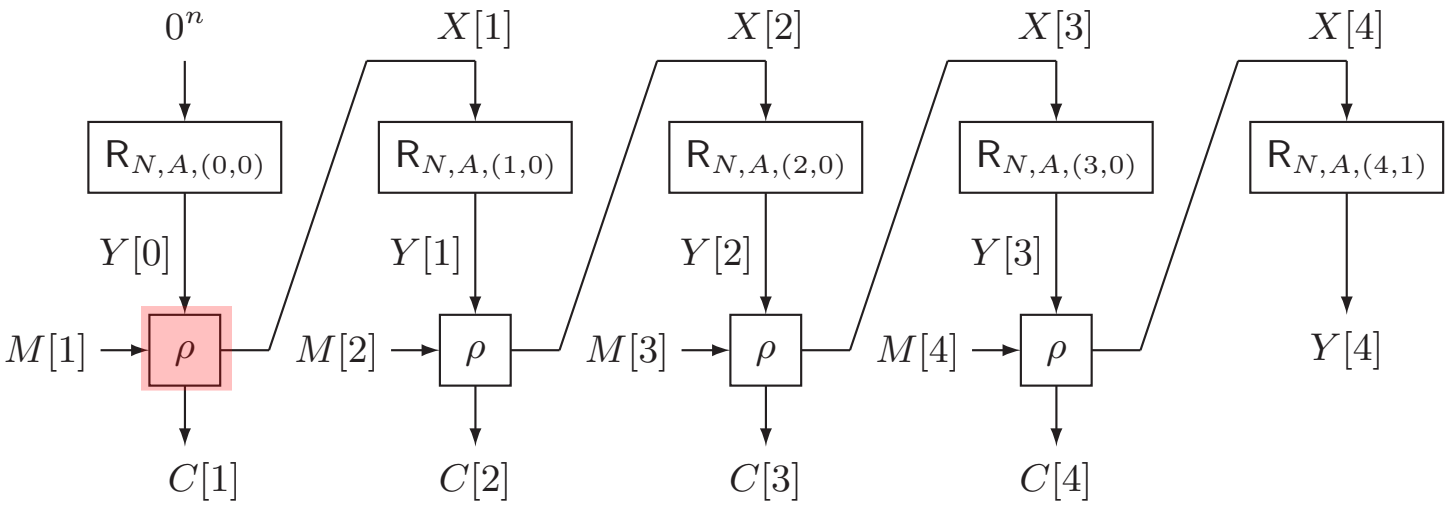
Easy to Understand COFB

iCOFB Construction



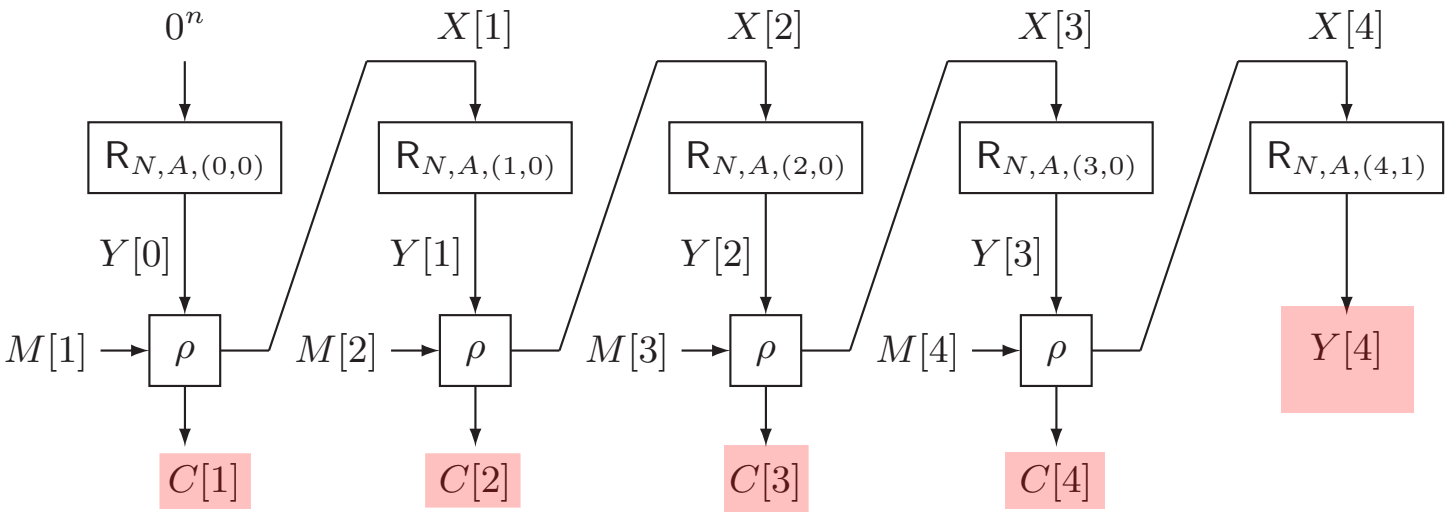
- $\mathsf{R}_{N,A,(a,b)}$: *Tweakable random function*
- $\forall N, A, (a, b)$, $\mathsf{R}_{N,A,(a,b)} : \mathcal{B} \rightarrow \mathcal{B}$

iCOFB Construction



- ρ : *Linear Feedback Function*

iCOFB Construction



- $CT = (C[1], C[2], C[3], C[4]), \quad Tag = Y[4]$

Linear Feedback Function : ρ

- For $\rho : \mathcal{B} \times \mathcal{B} \rightarrow \mathcal{B} \times \mathcal{B}$, $\exists \rho^{'}$
- *Correctness Condition* for encryption,
  - $\forall Y, M \in \mathcal{B}$, $\rho(Y, M) = (X, C) \Rightarrow \rho^{'}(Y, C) = (X, M)$
- ρ ensures given (Y, C): M should be *uniquely* computable
- Example : $\rho = \begin{pmatrix} G & I \\ I & I \end{pmatrix}$, $\rho^{'} = \begin{pmatrix} I + G & I \\ I & I \end{pmatrix}$, G is *invertible*

ρ and ρ'

ρ: During Encryption

- $\begin{pmatrix} X[i] \\ C[i] \end{pmatrix} = \begin{pmatrix} E_{1,1} & E_{1,2} \\ E_{2,1} & E_{2,2} \end{pmatrix} \begin{pmatrix} Y[i-1] \\ M[i] \end{pmatrix}$
- If ρ Satisfies the correctness condition then $E_{2,2}$ must be *inv*

ρ': During Decryption

- $\begin{pmatrix} X[i] \\ M[i] \end{pmatrix} = \begin{pmatrix} D_{1,1} & D_{1,2} \\ D_{2,1} & D_{2,2} \end{pmatrix} \begin{pmatrix} Y[i-1] \\ C[i] \end{pmatrix}$
- $D_{1,1} = E_{1,1} + E_{1,2}.E_{2,2}^{-1}.E_{2,1}$, $D_{1,2} = E_{1,2}$
- $D_{2,1} = E_{2,2}^{-1}.E_{2,1}$, $D_{2,2} = E_{2,2}^{-1}$
- ρ is *Valid* if both $(C1)$ $E_{2,1}$, $(C2)$ $D_{1,2}$ and $(C3)$ $D_{1,1}$ invertible

Privacy and Authencity for iCOFB

- $(C2) \Rightarrow \forall Y, C \neq C',\ D_{1,1}.Y + D_{1,2}.C \neq D_{1,1}.Y + D_{1,2}.C'$
- $(C3) \Rightarrow \rho$ is invertible (for correctness $E_{2,2}^{-1}$ is invertible). Hence,

$$\Pr[Y \xleftarrow{\$} \mathcal{B} : D_{1,1}.Y + D_{1,2}.C = X] = 2^{-n},\ \forall (C, X) \in \mathcal{B}^2$$

Theorem

If ρ is valid then for adversary $\mathcal{A}$ making q encryption queries and q_f forging attempts having at most ℓ_f many blocks, we have

$$\mathbf{Adv}^{\mathrm{priv}}_{iCOFB}(\mathcal{A}) = 0, \quad \mathbf{Adv}^{\mathrm{auth}}_{iCOFB}(\mathcal{A}) \leq \frac{q_f(\ell_f + 1)}{2^n}.$$

Design Rationale and Challenges

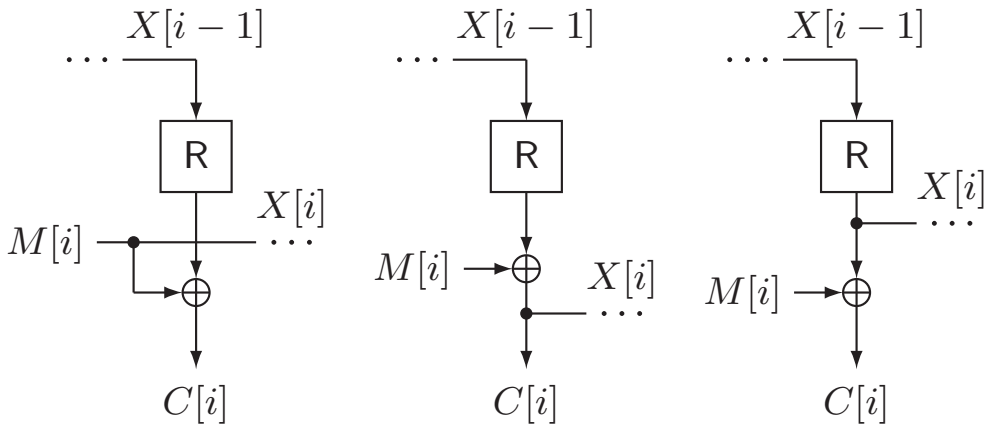
COFB : An instantiation of iCOFB

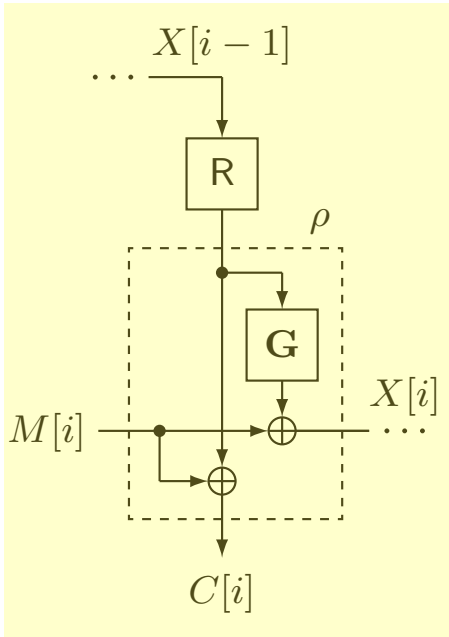
- Instatiation of iCOFB is possible by standard method (like XE mode)
- But results in 2 state memories

- Here, we considered *half* tweak (only Half-bit mask)
- Sufficient for *standard* security bound

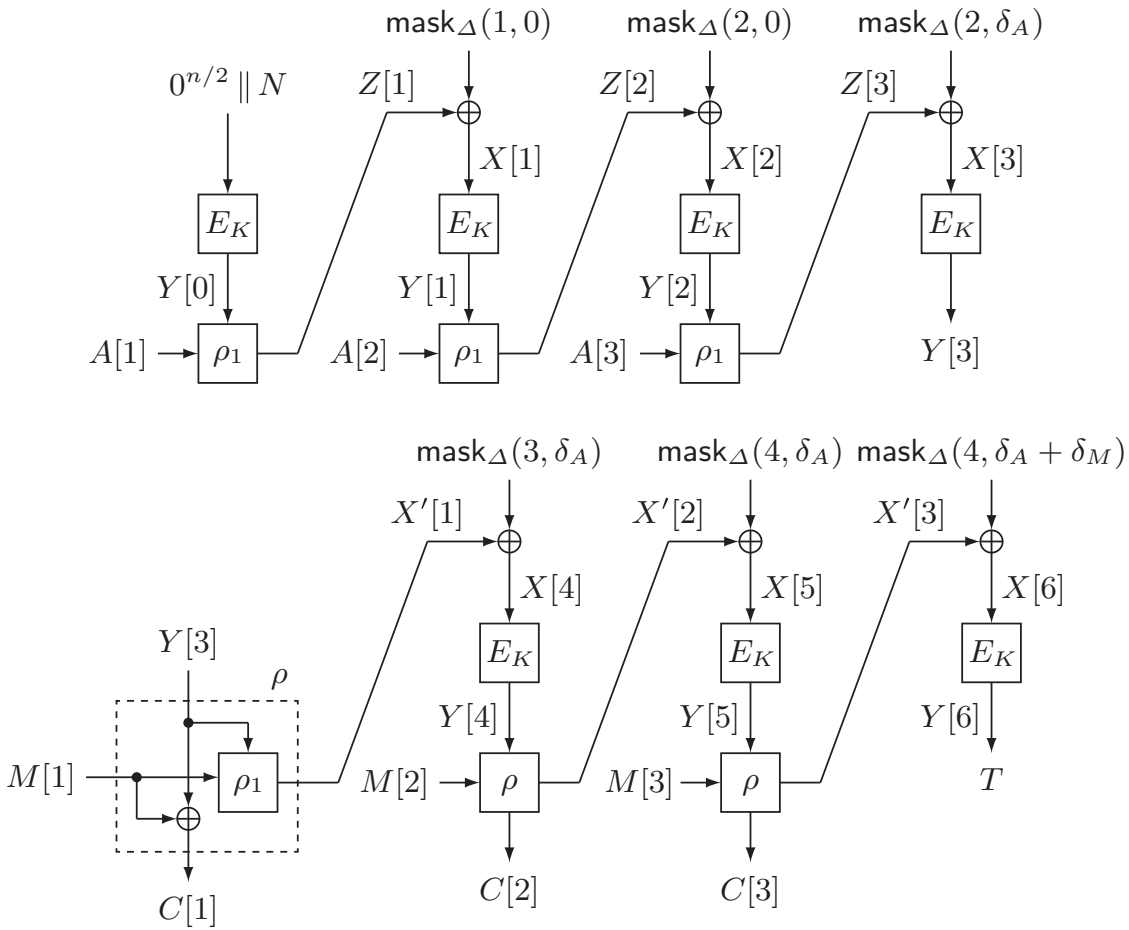
- The proof for COFB is not the same as XE based iCOFB
- Proof based on *specific* design (w/o iCOFBs security bound)

COFB (Combined Feedback) Mode





COFB Authenticated Encryption Scheme



COFB Authenticated Encryption Mode

Underlying Blockcipher

- We use *AES*-128 as the underlying blockcipher
- $n = 128$

mask Function

mask - mask is simple tweak update function

ρ_1 and ρ Functions

ρ_1 and ρ Functions - Simple Linear Feedback Functions.

Last Block has *different* tweak

Tweak Function

- Tweak - *Nonce* dependent 64 -bit secret value.
- Standard Tweak size - 128-bits. Here 64-bit is sufficient
- Computed/ updated by $\text{mask}_\Delta(a, b) = \alpha^a(1+\alpha)^b.\Delta$
- $(a, b) \in [0..L] \times [0..4]$, L be the message length in blocks
- α - primitive element in $\mathbb{F}_{2^{64}}$

Linear Feedback Function

- Two feedback function - ρ_1 and ρ
- $\rho_1(y, M) := G \cdot y \oplus M$ and $\rho(y, M) = (\rho_1(y, M), \quad y \oplus M)$
- $G : (y_1, y_2, y_3, y_4) \rightarrow (y_2, y_3, y_4, y_4 \oplus y_1)$

$$G_{n \times n} = \begin{pmatrix} 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \\ I & 0 & 0 & I \end{pmatrix}$$

Security Level for COFB

Security Bounds for privacy

- *Birthday* Bound
- 64-bit for *Privacy*

Security Bounds for Authenticity

- *Birthday* Bound
- 64-bit for *Authenticity*

Important Features of COFB

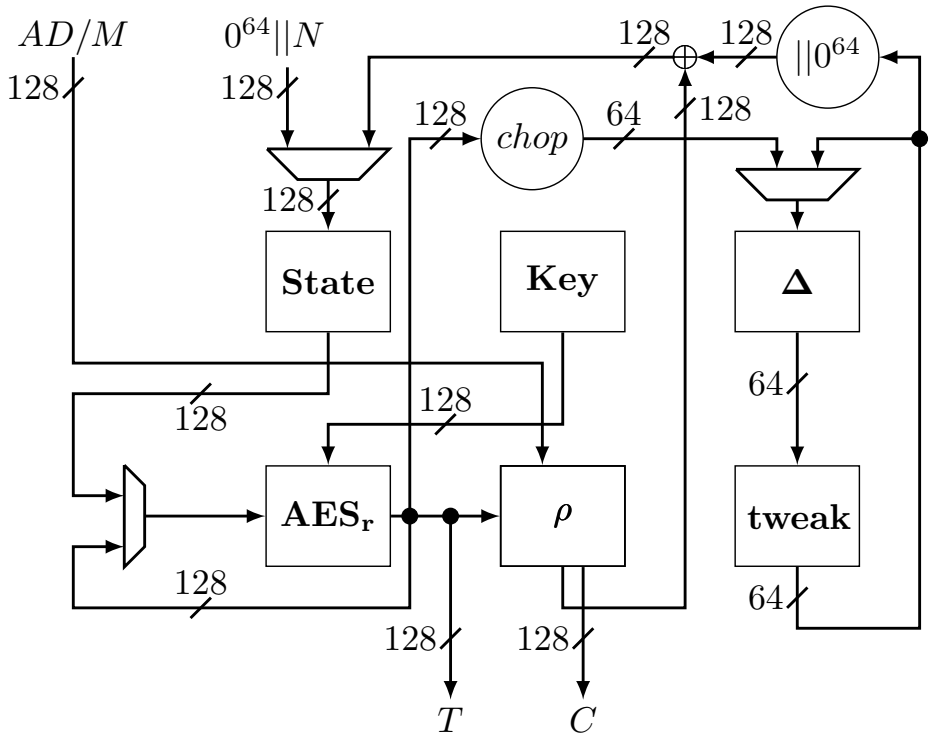
Advantages

- It is a "*Rate* − 1" construction.
- Very low *state size*. Only $1.5n + k$ (n:blockcipher size)
- Very *Flexible* Mode (*Any* Blockcipher)
- It is *inverse*-*free*
- *Simple* yet highly *effective* Linear Feedback
- Very Lightweight and Consumes *Low* Hardware area

Limitations

- *Both* the encryption and decryption are completely *serial*

COFB-Base Architecture



COFB-Base Architecture Properties

- No *pipelined* register
- *Serial* processing of data
- Processes 128-bits per 12 clock cycles
- Uses Very *Low* Storage Registers
- *Minimum* Hardware Area Among All the Known Implementations

COFB FPGA Implementation

Informations

- VHDL
- PLatform - Virtex 6 Under Xilinx 13.4
- Target Device - xc6vlx760

Base Implementation Results

- Area : 722 Slice Reg, 1075 LUTs and 442 Slices
- Frequency : 267.20 MHZ, Throughput : 2.85 Gbps

Benchmarking of COFB

A *fair* comparison is needed

A fair comparison based on *GMU* inteface to be done in future

Conclusion

- COFB : *Blockcipher* based *AE*
- 64-bit privacy and 64-bit authenticity.
- *Low Area* AE and can be used in low resource *embedded device*

Thank you