Lightweight Cryptography and Classification of AEAD Modes

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tcg crest

Inventing Harmonious Future

Content

- Introduction to Authenticated Encryption
- Motivation of Lightweight Cryptography
- A Discussion on NIST LwC Project
- Classification of lightweight AEAD Modes

I: An Introduction to Authenticated Encryption

The Popular Story: **Encryption**

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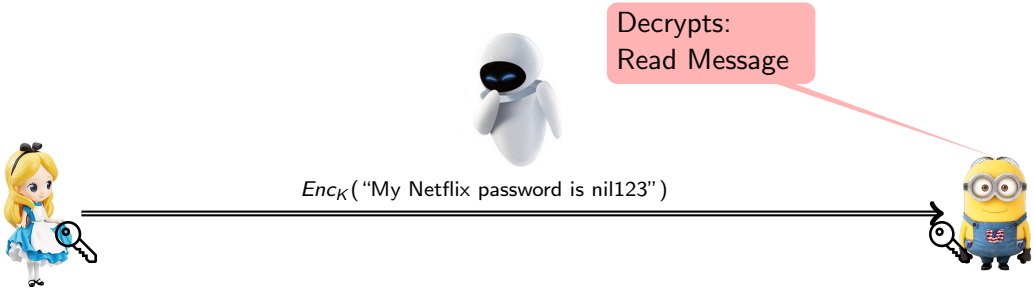
3. Data Privacy: Only Bob can decrypt. No information (other than length) about plaintext is leaked from ciphertext

The Popular Story: **Encryption**

$Enc_K(\text{“My Netflix password is nil123”})$

The Popular Story: **Encryption**



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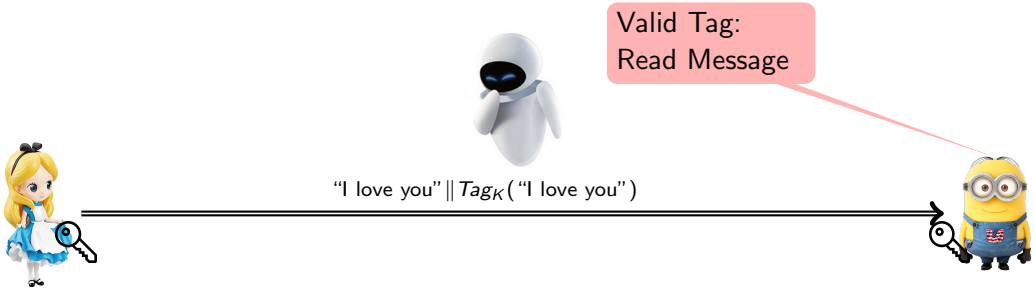
3. Data Integrity: Bob can verify valid tag and can reject all tampered tag

The Popular Story: **Authentication**

"I love you" $\|\, Tag_K(\text{"I love you"})$

The Popular Story: **Authentication**



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"I love you" $\| Tag_K($ "I love you" $)$

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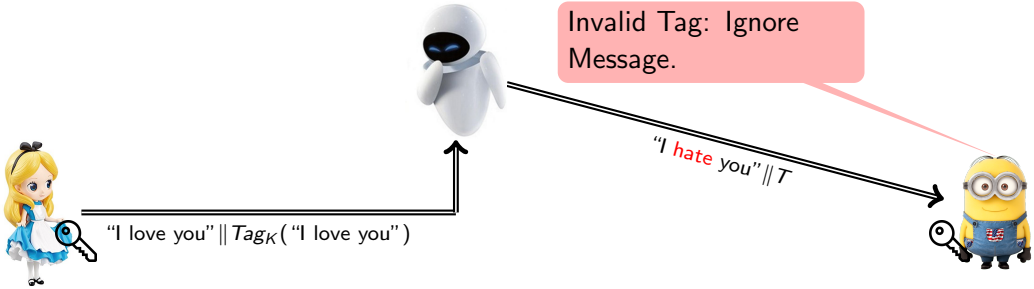
The Popular Story: **Authentication**



Authenticated Encryption

Authentication + Encryption

Why Authenticated Encryption?

Chasing the Gangstar

Inspector Alice wishes sub-inspector Bob to move his check point to a different location

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- Data *Privacy*: The updated check point should remain *confidential*
- Data *Authenticity*: Alice sends the updated check point and it has not been modified in transit

Why Authenticated Encryption?

Covid Report

Doctor Alice wishes to send the covid report M of Bob to the medical database

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- Data *Authenticity*: Alice prepares the report and the report was not modified in transit

Why Authenticated Encryption?

The Annual Evaluation

Prof. Alice wishes to inform the semestral marks to her students

- Data *Privacy*: Bob's marks should remain *confidential*
- Data *Authenticity*: Alice sends the marks and the marks have not been modified in transit

Authenticated Encryption with Associated Data (AEAD)

AEAD Algorithm

$$\mathcal{AE}(K, AD, M, N) \rightarrow (C, T)$$

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- Requires data authenticity, not privacy

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- Requires data authenticity, not privacy

What is Nonce?

- An arbitrary number used only *once*. Example: *Counter*
- Used to generate randomness

Authenticated Encryption with Associated Data (AEAD)

Verified Decryption Algorithm

$$\mathcal{VD}(K, AD, C, T, N) \rightarrow M/\perp.$$

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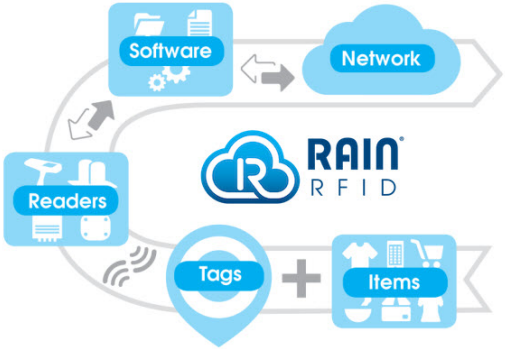
A Note on Verified Decryption

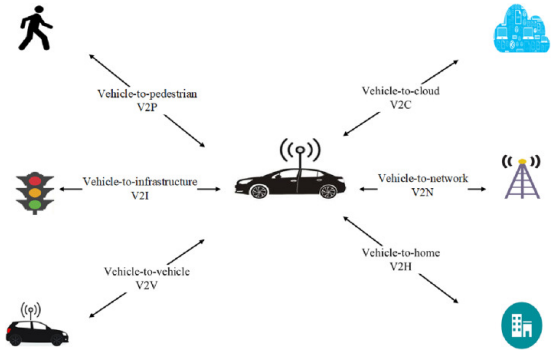
- Plaintext is only released after verification is successful
- Otherwise, the algorithm aborts
- However, the ordering of verification and decryption may vary

II: An Introduction to Light-weight Cryptography

Lightweight Cryptography: Use in Rain RFID Tags

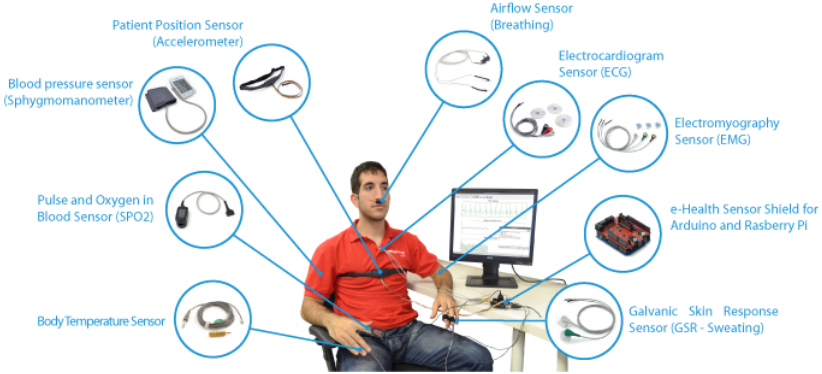


Lightweight Cryptography: Use in Vehicles



Lightweight Cryptography: Use in Smart Home

Lightweight Cryptography: Use in Medical Sensors



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Subfield of Cryptography that aims to provide crypto solutions tailored to constrained environments

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$$\text{Lightweight} = \text{Light} + \text{Weight}$$

Weight of an Algorithm

A property of its implementation depending on different metrics of the target platform

Weight of An Algorithm

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General Purpose Crypto vs Lightweight Crypto

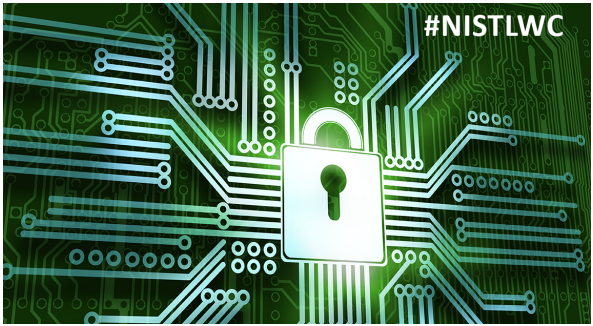
General Purpose Crypto

- Used in several applications
- A proper trade-off of various metric: area, speed, throughput, energy etc

Lightweight Crypto

- Used for dedicated resource constraint environment
- Lack of Crypto standards suitable for such devices.

III: A Brief Overview on NIST LwC Project



NIST LwC Project: Timeline

- Aug 2018: Call for Algorithms
- Mar 2019: First Round Submission
- Aug 2019: Declaration of Second Round Candidates
- Sep 2019: Second Round Submission
- Dec 2020: Declaration of Third Round Candidates
- End of 2021: Final Portfolio

NIST LwC Project: Requirements

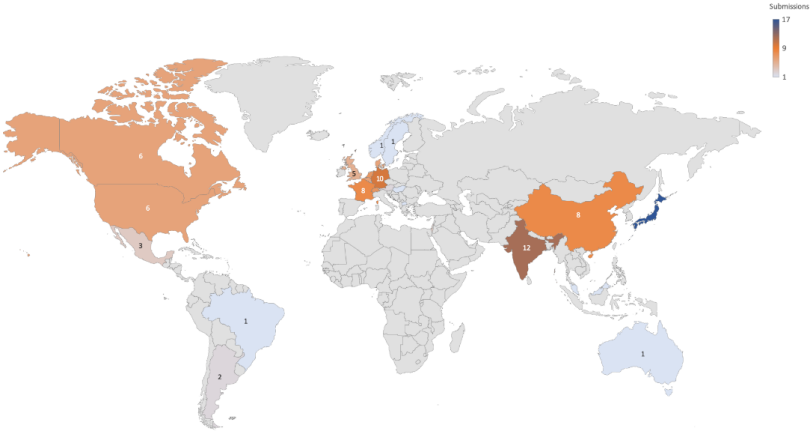
- Perform significantly better in constrained environments (HW and SW platforms)
- Efficient for short messages
- Implementations should have cheap countermeasures against side channel attacks, and fault attacks
- Scope: AEAD with optional hashing functionality

NIST LwC First Round Candidates

- Total 57 submissions in Round 1 (12 from India)

*Figure Courtesy: Meltem Sonmez Turan

NIST LwC Submission Statistics



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NIST LwC Second Round Candidates

- Total 32 candidates moved to Round 2 (10 from India)

ACE	ASCON	COMET	DryGASCON	Elephant	ESTATE
ForkAE	GIFT-COFB	Gimli	Grain-128 AEAD	HyENA	ISAP
KNOT	LOTUS-AEAD & LOCUS-AEAD	mixFeed	ORANGE	Oribatida	PHOTON-Beetle
Pyjamask	Romulus	SAEAES	Saturnin	SKINNY-AEAD	SPARKLE
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All the 10 submissions are co-designed by **Prof. Mridul Nandi**

IV: Lightweight AEAD: Features and Design

Some Relevant Features of AEAD Modes

Single-Pass

- Make only one pass through the data, simultaneously doing what is needed to ensure both privacy and authenticity
- Computational cost for single-pass schemes are about half of a two-pass scheme, and hence efficient

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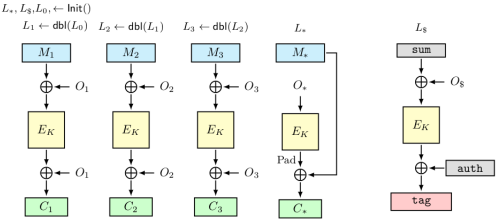
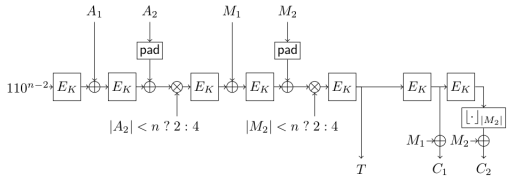


Single Pass



Two Pass

Some Relevant Features of AEAD Modes

On-line

- Encryption produces cipher-text blocks on the fly, and before subsequent plain-text blocks are known
- Ensures that no additional memory is needed to store intermediate results for later use
- Useful in real-time streaming protocols as it reduces the end-to-end latency

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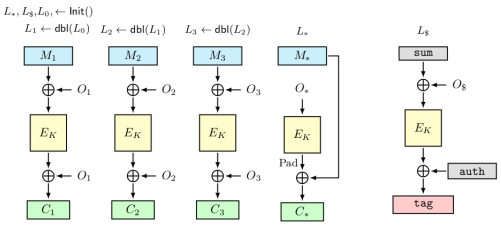

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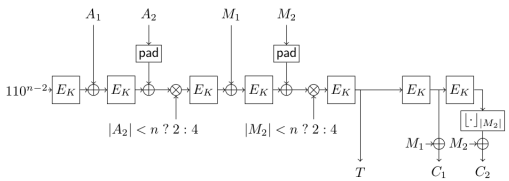

Not On-line

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Parallel

- All the ciphertext blocks can be computed in parallel
- Allows both H/W and S/W acceleration proportional to the available computational unit
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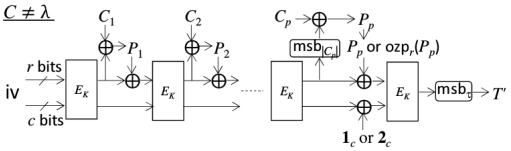
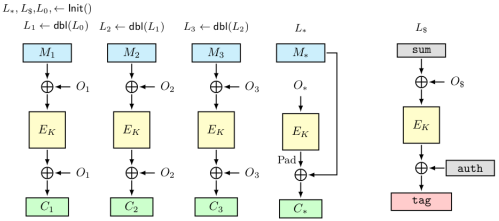


Sequential



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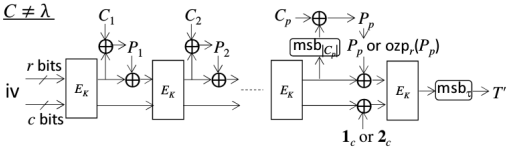

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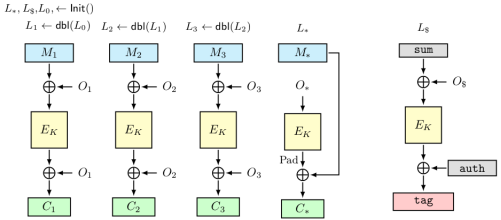

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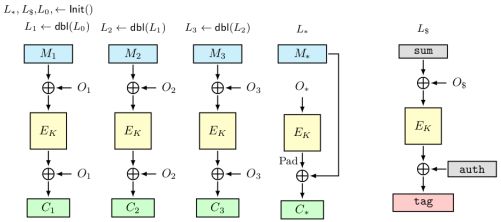
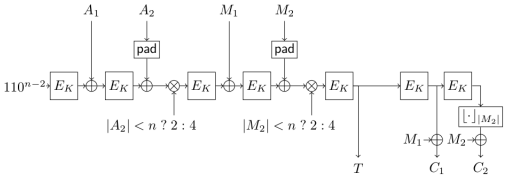


State size: $3n + k$ bits



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- Rate of an AEAD mode can be at most 1
- Constructions with higher rate reduces latency, and particularly beneficial to obtain higher speed

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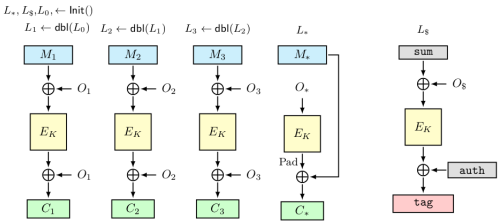
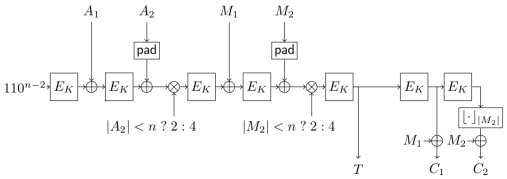


Rate: 1



Rate: 0.5

Some Relevant Features of AEAD Modes

Optimal (Primitive Invocation)

- Uses the minimum possible number of non-linear invocations
- The bound is given in [Chakraborti et al., JMC 18]:
  - Nonce based AEAD: $(a + m + 1)$
  - Deterministic: $(a + 2m)$
- Makes a construction efficient for short messages and reduces the latency

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- Makes a construction efficient for short messages and reduces the latency

Efficient Static AD Processing

- In many scenarios, AD remain static over the course of a communications session
- Efficient static AD processing use a pre-processed computed value instead of whole computation

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Nonce Misuse Resistance

- Provides security even if nonce is repeated, or even without nonce
- Well suited for lightweight applications where storing counter or generating random number may be difficult to implement

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Integrity under RUP

- Verified Decryption: Plaintext is released after verification
- Small buffer size may force decryption algo to release plaintext before verification
- This gives an adversary additional power, which may be exploited for forging

Mode Classification

- Parallel Mode
- Feedback based Mode
- SIV Mode
- Sponge Mode
- Stream Cipher Mode

Parallel Modes

- Inputs of the block ciphers depend on the message and not on the previous block cipher outputs or cipher texts, hence parallelization in the computation between distinct block cipher calls
- Typically Used in low-latency scenarios as well as for obtaining good performance from both high-speed hardware and commodity processors
- The parallel design allows to efficiently process subsequent message blocks exploiting the CPU pipeline and multi-threading techniques

Parallel Modes: Design Principle

- The design principles follow the ECB structure
- To ensure (i) privacy within a message and (ii) privacy within two messages, some additional masking state depending on the value of the nonce and the block number

Parallel Modes: Design Principle

Typical Choices:

- Xor-Encrypt-Xor paradigm
- tweakable block ciphers with tweak defined as a pair (nonce, block number)

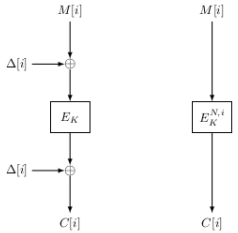
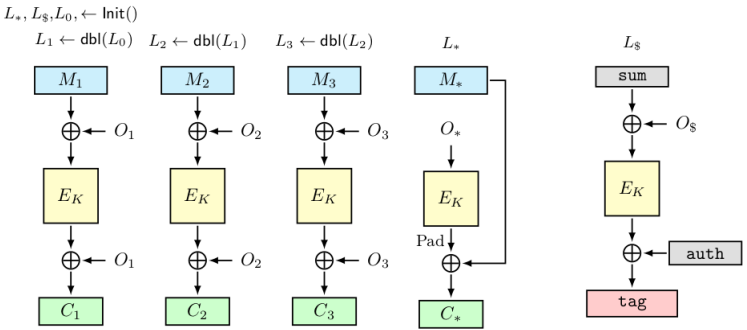


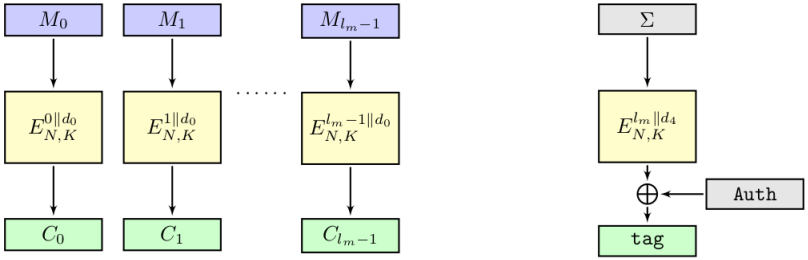
Figure: Parallel Mode of Encryption: (a) OCB, (b) ΘCB

Example1: Pyjamask (OCB Style Encryption)



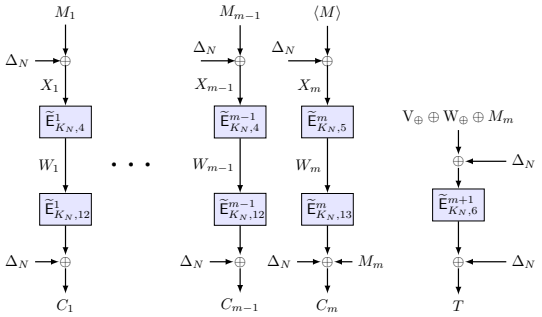
- Block Cipher based, Parallel, Online, Rate-1
- Birthday bound secure, No RUP Security

Example2: Skinny AEAD (ΘCB Style Encryption)



- Tweakable Block Cipher based, Parallel, Online, Rate-1
- Birthday bound secure, No RUP Security

Example3: LOCUS-AEAD (OCB Style with Intermediate checksum)

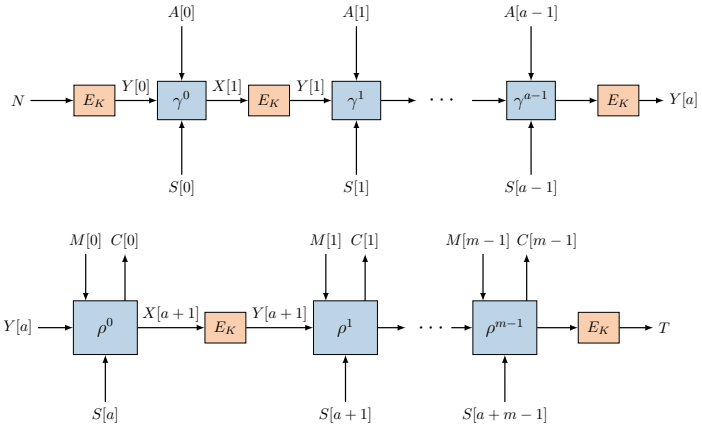


- Short-tweak TBC based, Parallel, Online
- Nonce-derived key for full security, Intermediate checksum to achieve RUP security

Feedback based Modes

- One of the most popular method of constructing area-efficient block cipher based AE
- Uses an affine function that takes a block cipher output and a plain text block to produce the corresponding cipher text block and an updated state which is used as the next block cipher input
- Reduce the state memory, at the cost of losing parallelizability
- Typically inverse-free and area-efficient for combined enc-dec implementations

Basic Structure of the Mode



Types of Feedback

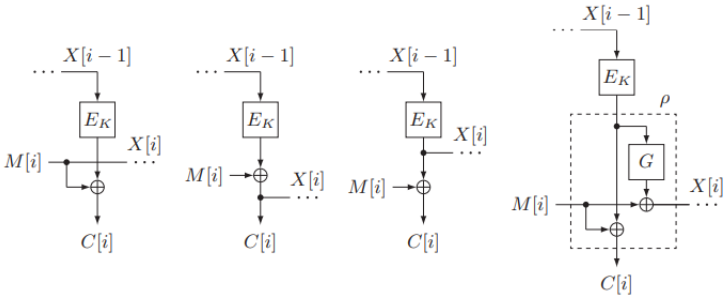


Figure: Hybrid Feedback functions: (a) PFB, (b) CFB, (c) OFB, (d) CoFB

Types of Hybrid Feedback

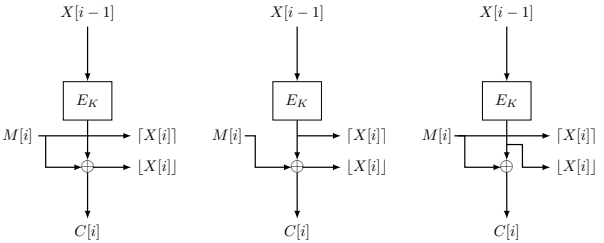


Figure: (a) PFB+CFB, (b) OFB+CFB, (c) OFB+PFB

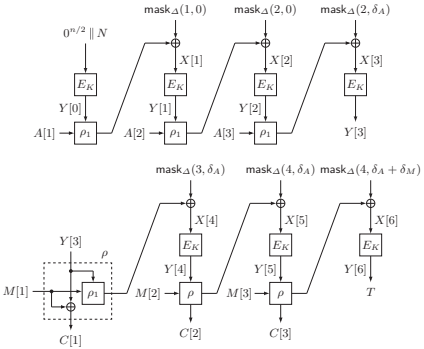
Investigating the Security of Rate-1 Feedback based AE

Encryption	Decryption	Additional states to achieve Security
PFB	CFB	n-bits
CFB	PFB	-
OFB	OFB	-
CoFB	CoFB	$n/2$-bits
HyFB (CFB+PFB)	HyFB (PFB+CFB)	$n/2$-bits
HyFB (CFB+OFB)	HyFB (PFB+OFB)	-
HyFB (PFB+OFB)	HyFB (CFB+OFB)	-

From Combined to Hybrid: Making Feedback-based AE Even Smaller [Chakraborti et al., ToSC 2020]

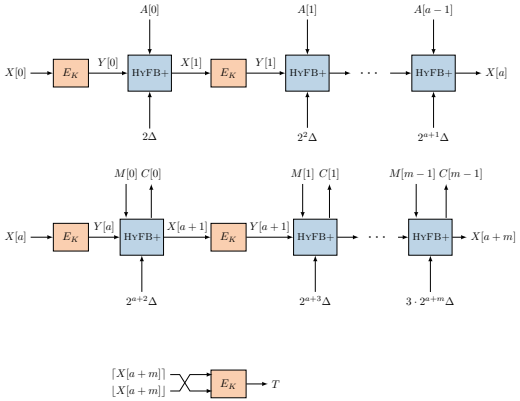
For any rate-1 feedback-based AE with additional state of τ-bits, there is an adversary that breaks the construction with query complexity 2^{τ}

Example1: COFB (A Mode with Combined Feedback)



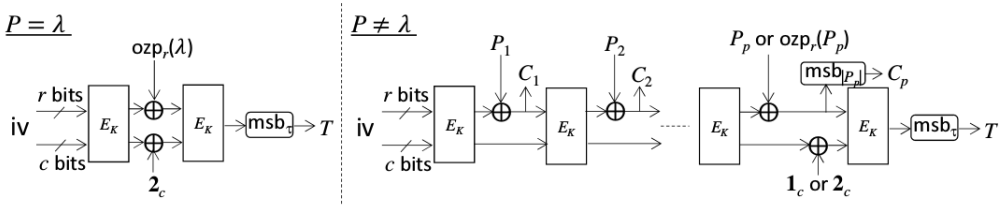
- Inverse-free, Rate-1, Efficient AD Processing
- State size: $1.5n$-bit (optimal for rate-1), XOR: $2n$-bit

Example2: HyENA (A Mode with Hybrid Feedback)



- Inverse-free, Rate-1, Efficient AD Processing
- State size: $1.5n$-bit (optimal for rate-1), XOR: n-bit

Example3: SAEAES (A Block-cipher based Sponge Variant)



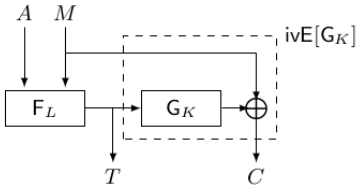
- Inverse-free, Rate-1/2, Efficient AD Processing
- State size: n-bit (optimal irrespective of rate)

SIV based Modes

- Provide maximal robustness to a lack of proper randomness or secure state
- Follows MAC-then-Encrypt structure, and hence two pass mode
- Typically obtain single-state implementation
- Excellent choice for short message processing

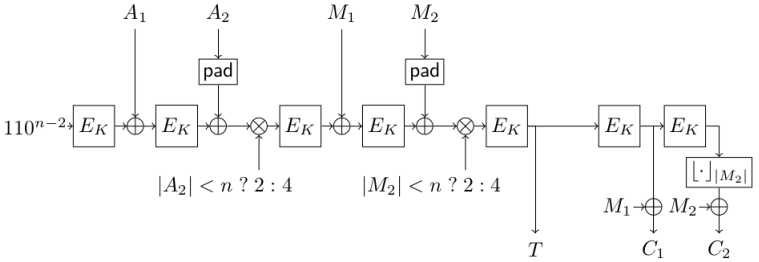
Design Principle

- Follow the MAC-then-ENCRYPT structure



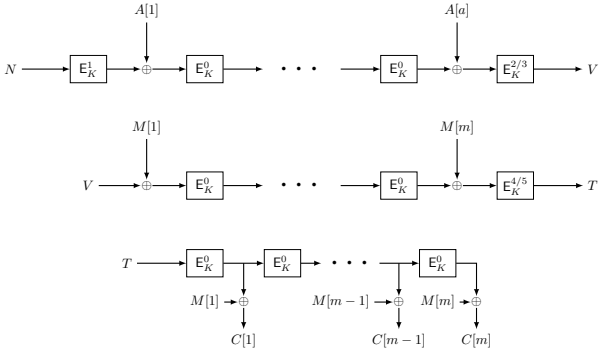
- A typical choice is CBC-type MAC (single-state implementation) follows by OTP or OFB with the tag as IV

Example1: SUNDAE



- Use CBC MAC with OFB encryption
- Single-state, Inverse-free, efficient for short messages

Example2: ESTATE

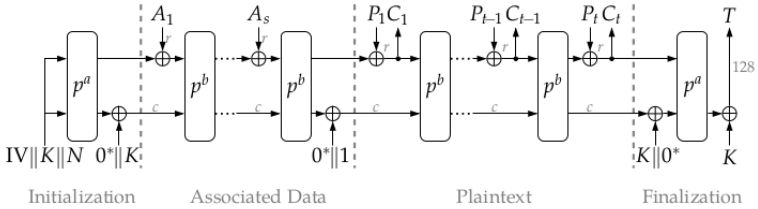


- Single-state, Inverse-free, efficient for short messages
- Use tBC to ensure RUP security, optimal block-cipher invocations

Sponge Modes

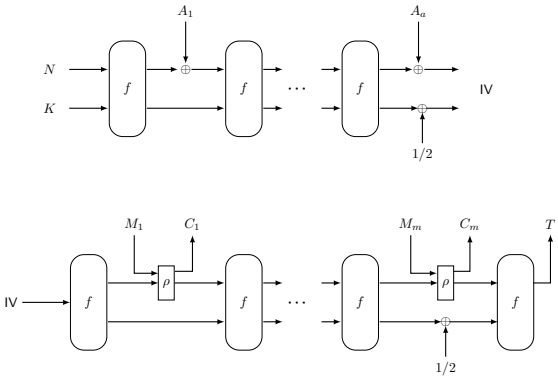
- Use public permutation instead of keyed permutation
- Employs duplex mode of operation - absorbs the data and then squeeze the ciphertext
- Has the advantage of key agility: no key-scheduling

Example1: ASCON (Simple Duplex type Sponge Mode)



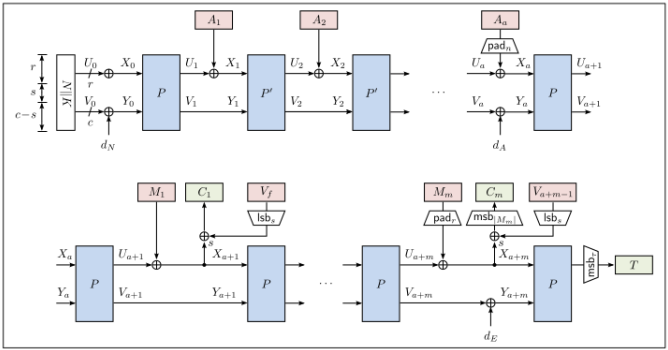
- Use simple duplex-sponge mode of operation with sponge rate 64-bit and sponge capacity 256-bit
- Achieves security of 128-bit

Example2: PHOTON-Beetle (Duplex Sponge Mode with Feedback)



- Uses duplex-sponge mode with a feedback function ρ with sponge rate 128-bit and sponge capacity 128-bit
- ρ plays the key role to achieve 121-bit security keeping the sponge capacity to 128-bit

Example3: Oribatida (Sponge with Ciphertext Masking)

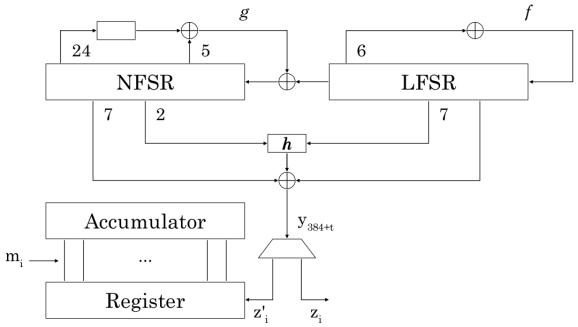


- A sponge with sponge rate 128-bit and sponge capacity 128-bit with 64-bit ciphertext masking
- The masking boosts the security and ensures resilience in RUP settings

Stream Cipher Modes

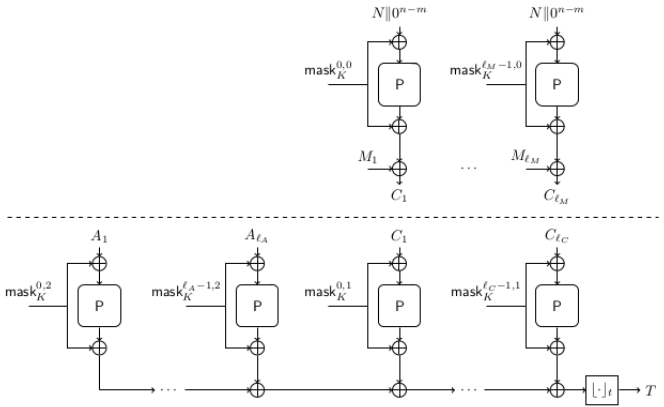
- Use a stream-cipher encryption as the basic mode
- Used to design fast and energy-efficient AEAD
- Typically, no additional states are reserved, and hence area-efficient
- Excellent choice for long messages

Example1: Grain AEAD



- Adopts the design of Grain-128 and Grain v1 and extends it for authentication

Example2: Elephant



- Use public-permutation to generate the key stream

Classification of NIST Round-2 Candidates

- Parallel Mode: LOTUS-AEAD and LOCUS-AEAD, PAEF (ForkAE), Pyjamask, SKINNY-AEAD
- Feedback based Mode: Comet, GIFT-COFB, HyENA, mixFeed, Romulus-N, SAEAES, SAEF (ForkAE), TinyJAMBU
- SIV Mode: ESTATE, Romulus-M, Sundae-GIFT
- Sponge Mode: ACE, Ascon, DryGASCON, Gimli, ISAP, KNOT, Orange, Oribatida, PHOTON-Beetle, Sparkle, Spix, Spoc, Spook, Subterrain, Wage, Xoodyak
- Stream Cipher Mode: Elephant, Grain-128 AEAD, Saturnin

Summary

- Authenticated Encryption - Motivation, Basic Idea

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- Lightweight Cryptography - Motivation

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- NIST LwC Project - Timeline and Progress

Summary

- Authenticated Encryption - Motivation, Basic Idea
- Lightweight Cryptography - Motivation
- NIST LwC Project - Timeline and Progress
- Classification of AEAD Modes based on Design

Thank You..!!! Questions???

Light-Weight Cipher Design Challenge 2020

Link: https://www.dsci.in/ncoe-light-weight-cipher-design-challenge-2020/