NIST Workshop on the Requirements for an Accordion Cipher Mode 2024

Efficient Instances of Docked Double Decker With AES, and Application to Authenticated Encryption

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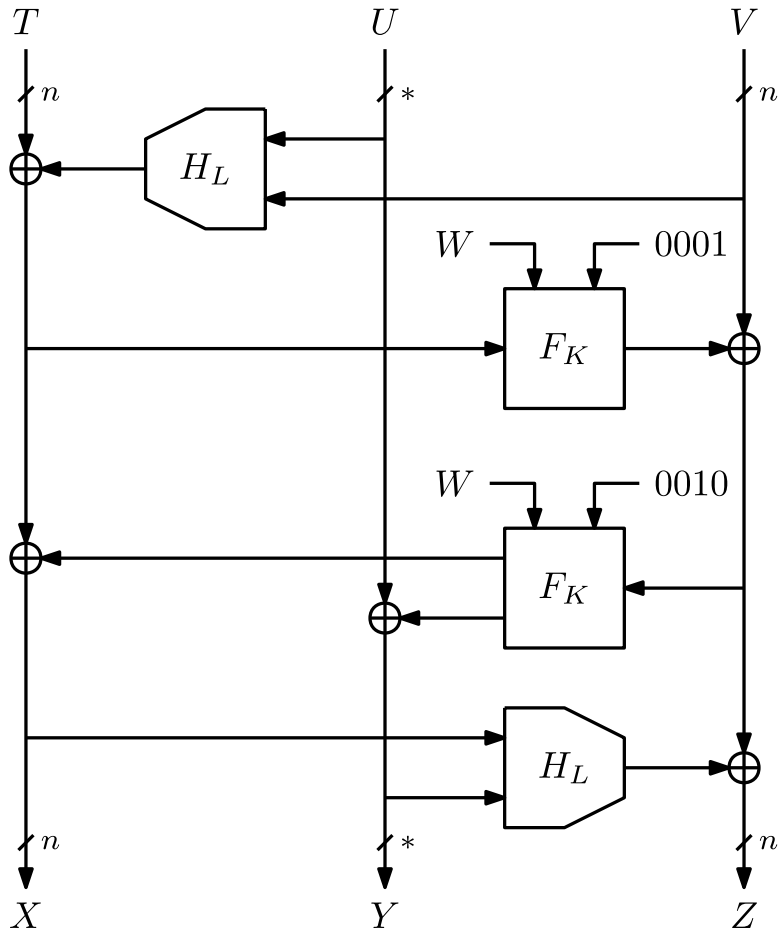
Overview

- The docked double decker
- 3 instances
  - ddd-AES
  - ddd-AES+
  - bbb-ddd-AES
- Design rationale
- Practical implications

The Docked Double Decker [GDM19]



- Building Blocks
  - F_K: stream cipher
  - H_L: universal hash
- Construction
  - Feistel-like structure
  - Outer lanes of fixed size
  - Inner lane of variable size

Security of the Docked Double Decker [GDM19]

- Generic security
  - Assume
    - H_L is ε-XOR-universal
    - F_K is PRF-secure
  - Adversary makes q queries and at most q_W queries per tweak W
  - Docked double decker is designed to be secure up to approximately

$$\sum_{W \in \{0,1\}^w} \binom{q_W}{2} \epsilon + \mathbf{Adv}_F^{\mathrm{prf}}(2q)$$

- Implications
  - Birthday bound secure in n in general case
  - Security can significantly increase when tweaks are not used too often

Our Goals and Hurdles to Overcome

- Goals
  - Build upon widely used components (NIST standards)
    - AES [DR02, DR20]
    - Operations in binary extension fields, e.g., like GHash [MV04]
  - Efficient in parallel use of components
  - Birthday bound and beyond-birthday bound secure instances that fit NIST's accordion idea
- Hurdles
  - AES
    - Not a tweakable blockcipher
    - 128-bit blocksize
    - Typical stream cipher modes only give birthday-bound security

Universal Hash Function Instantiation

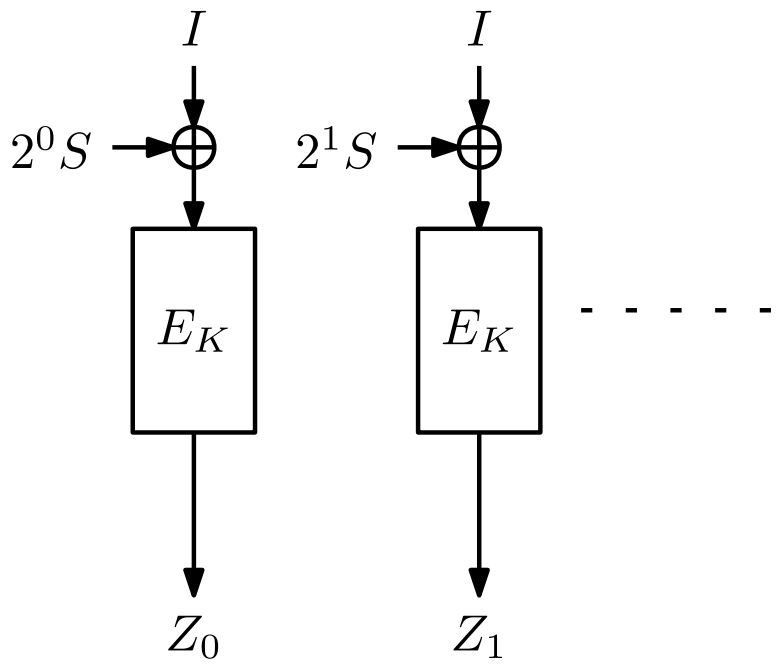
- Polyval [GLL17]
  - Operates on finite field $GF(2^{128})[x]/(x_{128} + x_{127} + x_{126} + x_{121} + 1)$
  - Defined as follows, for a padded message $(I_1, I_2, \ldots, I_s)$:

$$Polyval_L(I_1, I_2, \ldots, I_s) = \sum_{i=1}^{s} \left(L^{s-i+1} \cdot I_i \cdot x^{-128 \cdot (s-i+1)} \right)$$

  - We use zero padding with length extension
  - Polyval is ε-XOR-universal with $\varepsilon = \frac{m_{max}}{2^{128}}$ [GLL17]

Instantiation for Birthday Bound Secure ddd-AES

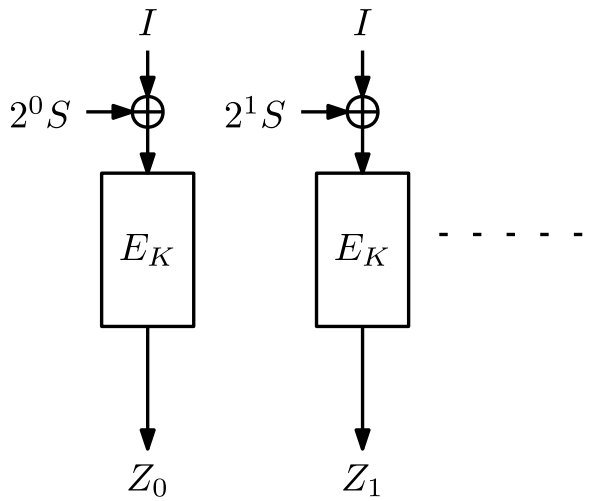
- XE-style [Rog04] tweakable blockcipher in counter mode
  - Let $S = E_K(B||W)$



  - Stream cipher (and thus ddd-AES) aims for $2^{n/2}$ PRF security

ddd-AES$^+$ for Variable Length Tweaks

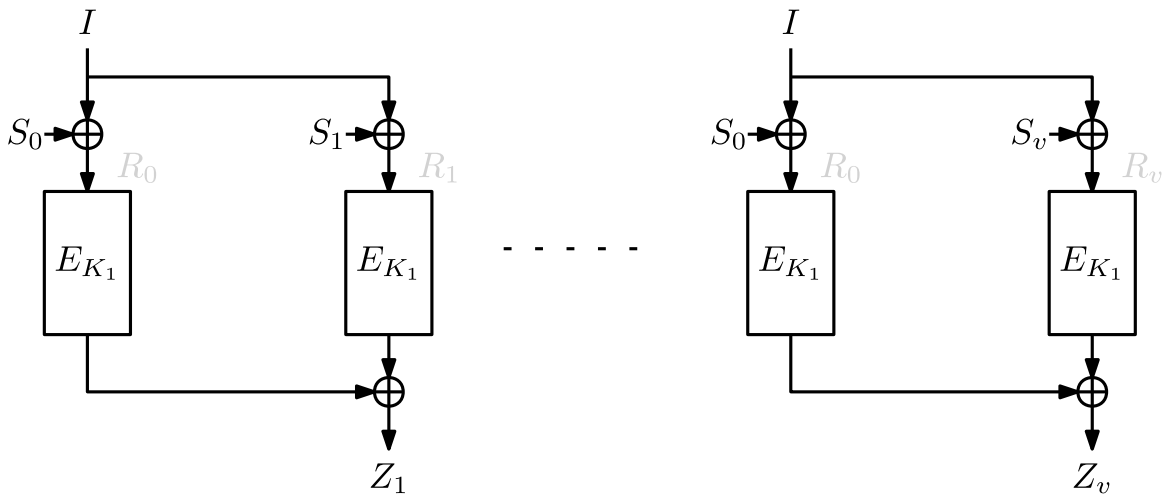
- XE-style [Rog04] tweakable blockcipher in counter mode
  - Pad B, W into $(W_0, W_1, \ldots, W_{l-1}||B'||0^*)$ with $B' = B \oplus 1000$
  - Let $S = E_K(W_0||0) \oplus E_K(W_1||1) \oplus \cdots \oplus E_K\left(W_{l-1}||B'||0^*||(l-1)\right)$



  - Stream cipher (and thus ddd-AES$^+$) aims for $2^{n/2}$ PRF security

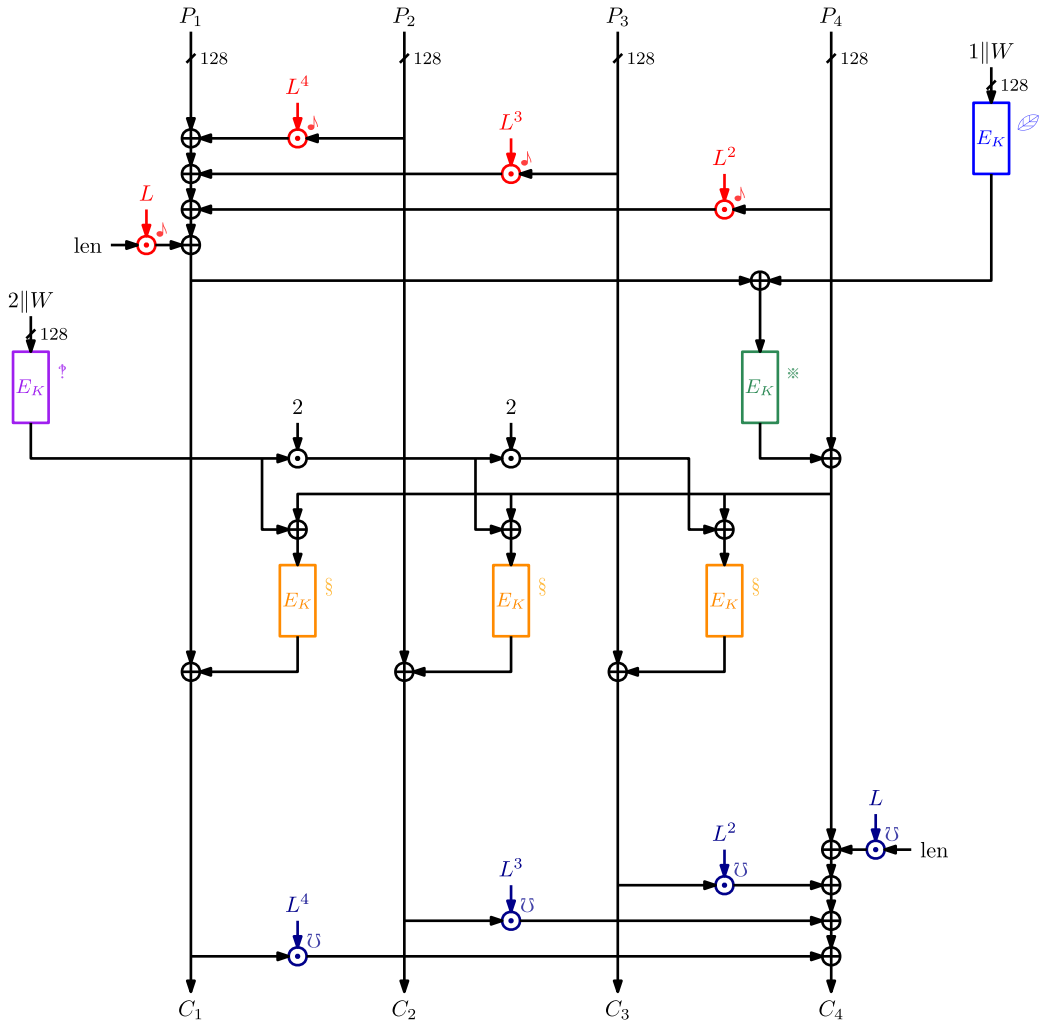
Instance Beyond Birthday Bound Secure bbb-ddd-AES

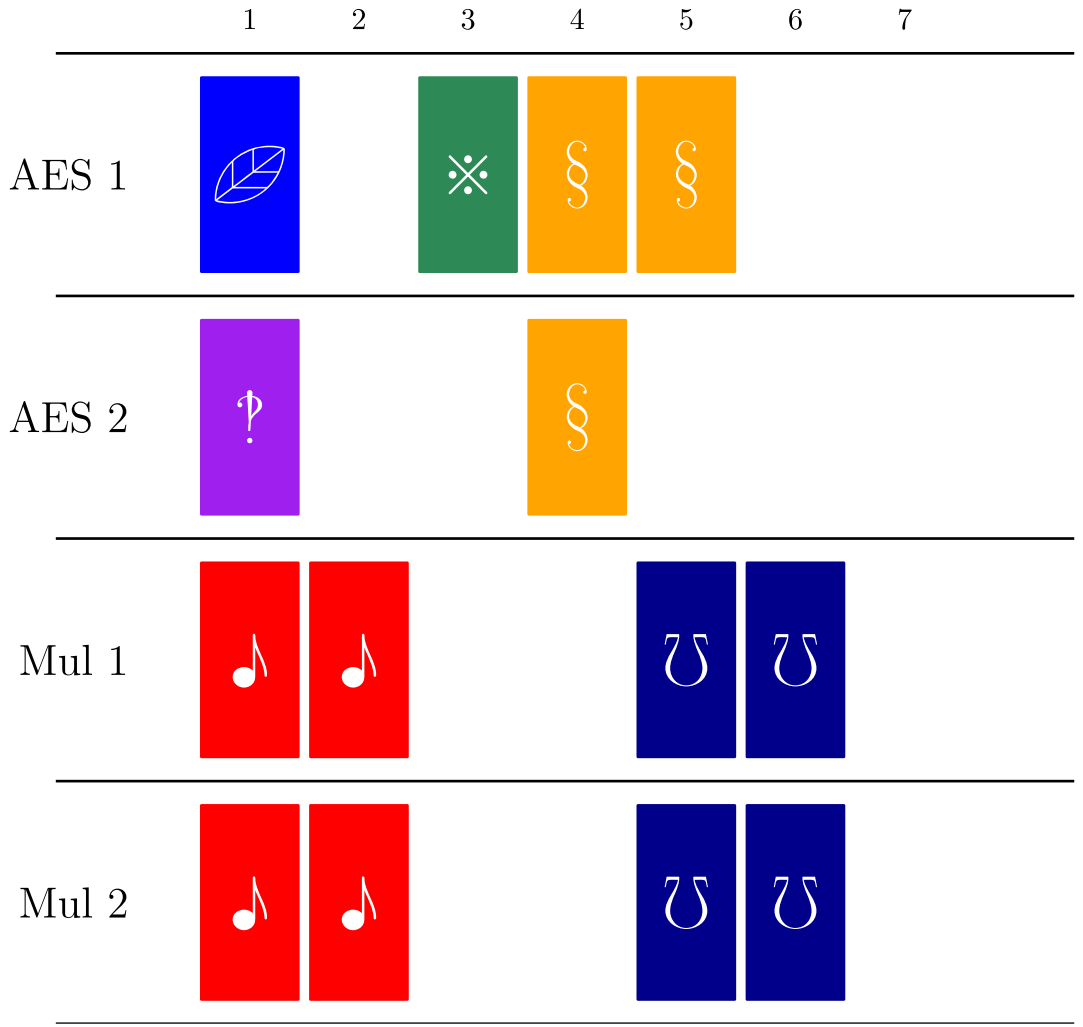
- $\widetilde{XORP}$ PRF in counter mode
  - $\widetilde{XORP}$: $XORP$ as in CENC [Iwa06] extended to include tweak
    - New and comes with separate security proof
    - Let $S_j = E_{K_2}(B||W||c||j)$



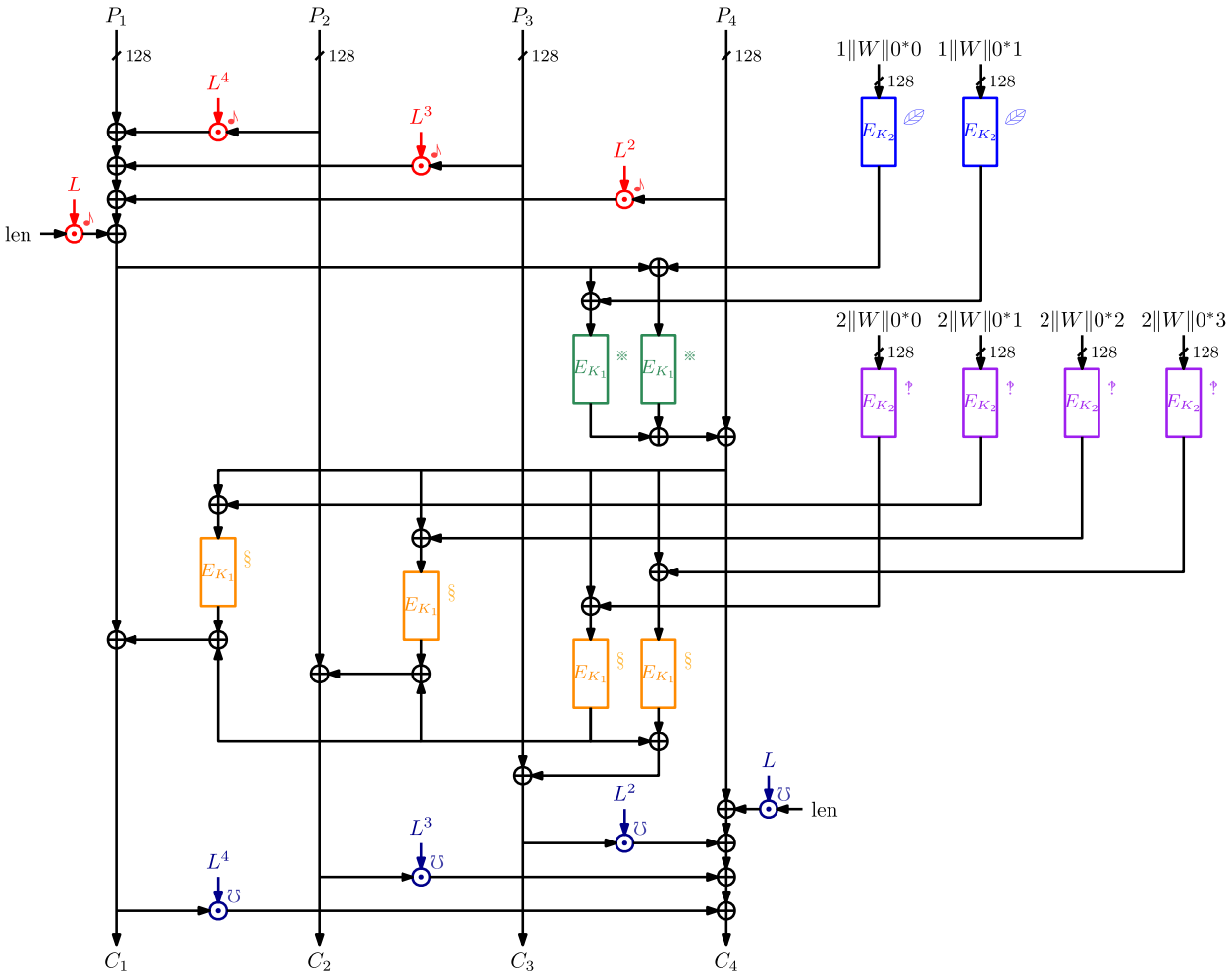
  - Stream cipher (and thus bbb-ddd-AES) aims for $2^{2n/3}$ PRF security when tweaks are not reused too often

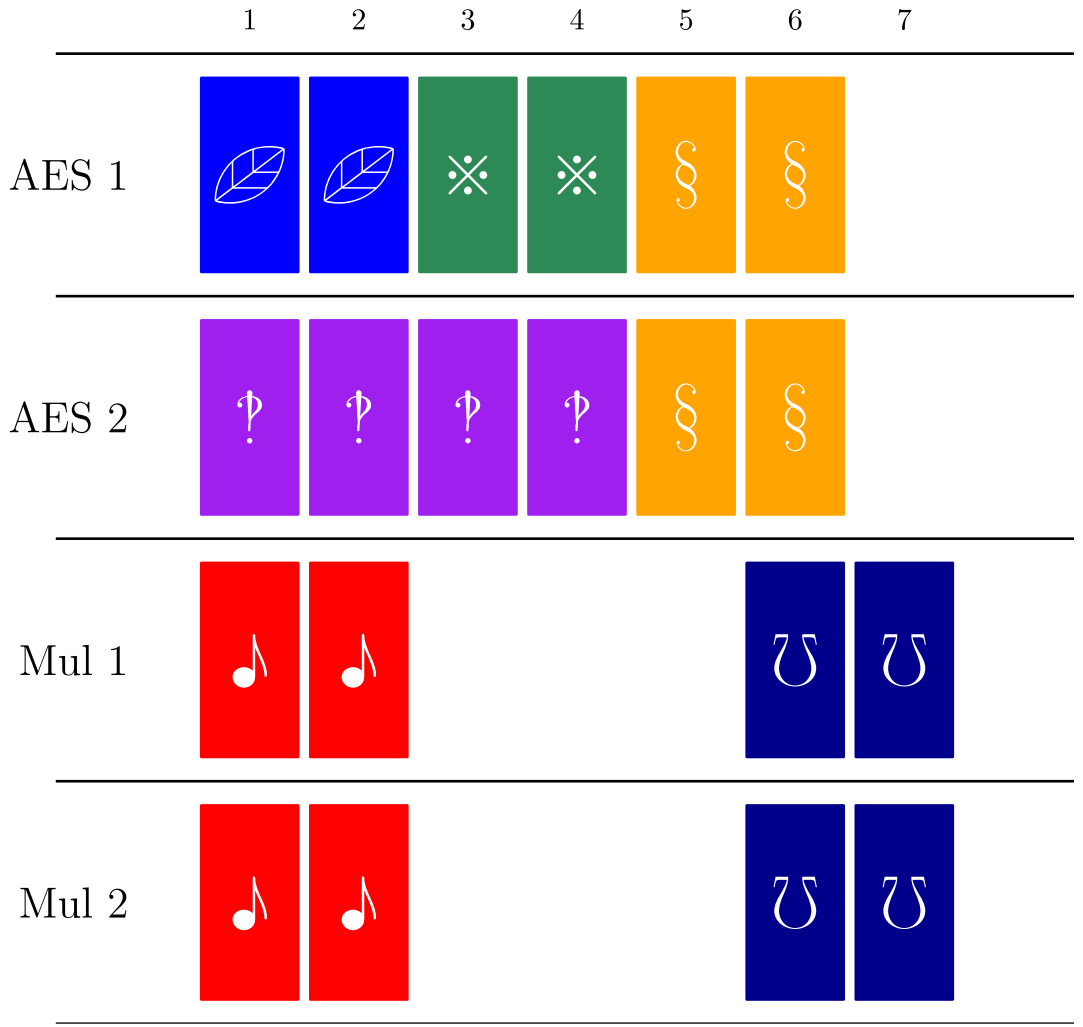
Design Rationale: ddd-AES with 512-bit blocks



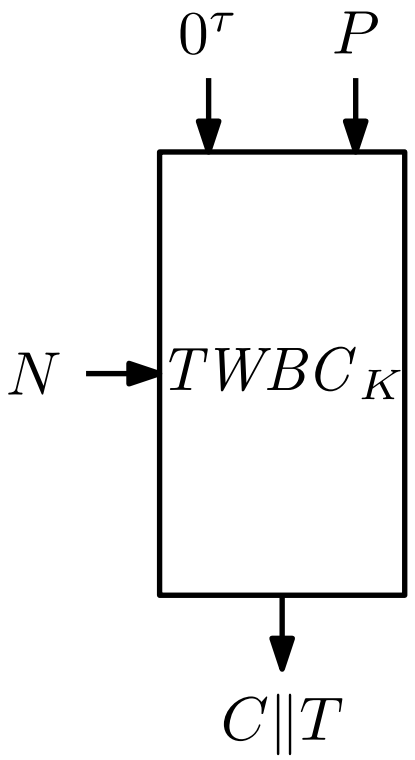


Design Rationale: bbb-ddd-AES with 512-bit blocks



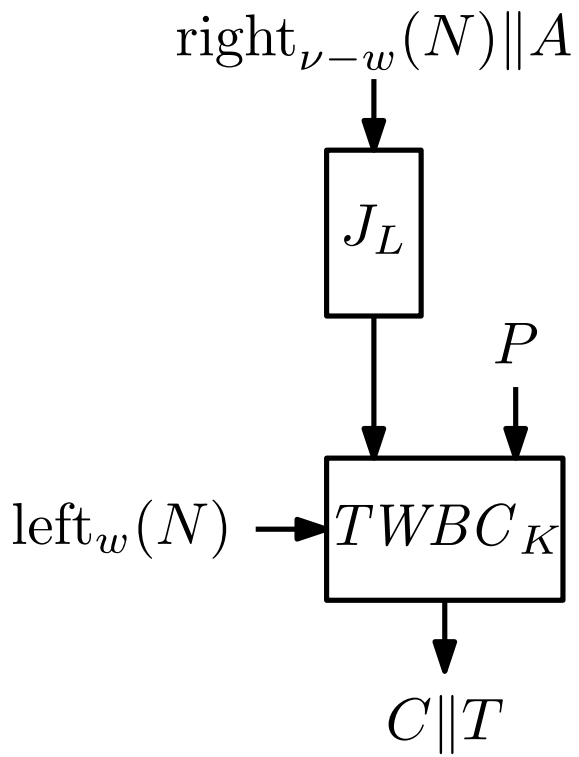


Basic Authenticated Encryption



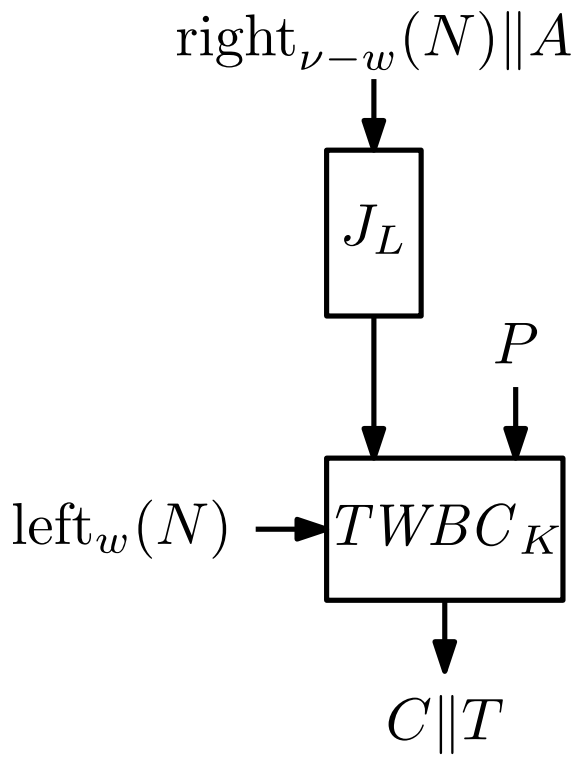
- Robust AE [HKR15]
  - Encryption:
    - Prepend τ zeros to P
    - Evaluate with $TWBC_K$ to obtain $C||T$
  - Decryption:
    - Decrypt $C||T$ using $TWBC_K^{-1}$
    - If the result starts with τ zeros: output P
- Limitations in our context
  - No associated data (ddd-AES$^+$ okay)

Advanced Authenticated Encryption with Associated Data (aaa)



- Building blocks
  - $TWBC_K$: tweakable wide blockcipher
  - J_L: universal hash
- Rationale
  - N partially entered into tweak
  - Rest of N and A hashed into τ -bit string

aaa: Security



- Nonce-respecting setting
  - $left_w(N)$ unique for each encryption query
  - Security analysis relies on fact that tweak to $TWBC_K$ is always new
- Random nonce setting
  - N is random for each encryption query
  - Security analysis relies on multicollision bound on the left w bits of the nonce
- Nonce-misusing setting
  - Birthday bound security

bbb-ddd-AES Example: Memory Encryption

- Assume advantage $\leq 2^{-32}$

- AES-XTS
  - 4 Terabyte of RAM (2^{40} lines) encrypted with one key
  - Write each line 2^{6} times

- bbb-ddd-AES
  - 4 Exabyte of RAM (2^{60} lines) encrypted with one key
  - Write each line 2^{11} times
  - And, e.g., 2^{20} lines 2^{30} times

aaa-bbb-ddd-AES Example: TLS

- AES-GCM
  - $2^{24.5}$ records of size up to $2^{14} + 1$ octets
  - Advantage below 2^{-57}

- aaa-bbb-ddd-AES
  - 2^{51} records of size up to $2^{14} + 1$ octets
  - Advantage below 2^{-57}
  - Plus other benefits like nonce-misuse resistance

Conclusion

- Introduced ddd-AES, ddd-AES+, and bbb-ddd-AES
- Schemes come with security reduction to AES
- Also introduced authenticated encryption mode aaa for TWBCs
- Paper at https://eprint.iacr.org/2024/084

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