Radboud University

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

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ASK 2024

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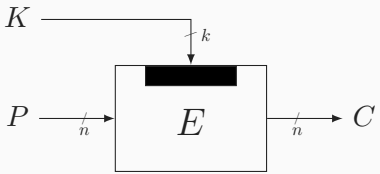
ESCADA

Introduction

Blockciphers



- Plaintext P encrypted to ciphertext C with secret key K
- Fixed block size

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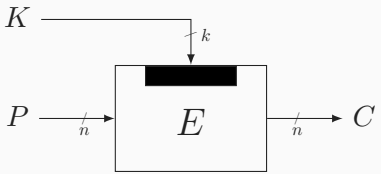
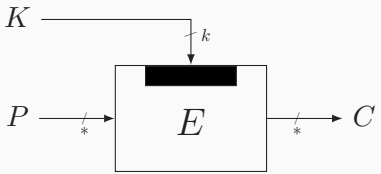


- Plaintext P encrypted to ciphertext C with secret key K
- Fixed block size
- In order to encrypt variable sized messages, we need a mode of operation
  - These modes require a nonce

Wide Blockciphers



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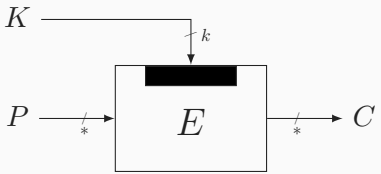
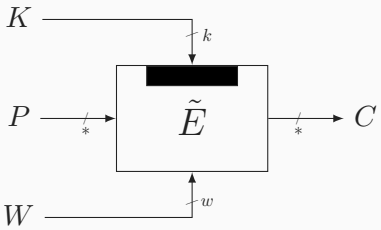


- Alternatively, we can design a wide block cipher
- A wide block cipher is a block cipher with a variable block size
- Every part of the output (ideally) depends on every part of the input

Tweakable Wide Blockciphers



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- Tweak W public, ciphertext completely changes with a different tweak

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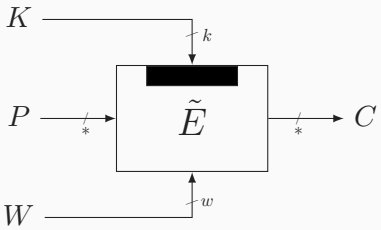

- A tweakable wide block cipher additionally has a tweak
- Tweak W public, ciphertext completely changes with a different tweak
- Useful for e.g. disk encryption, where every sector gets its own tweak

NIST's Incentive to Develop Accordion Mode

- March 2024: NIST announced quest for tweakable wide blockciphers
- There was a workshop (June 2024) aimed to discuss ideas on requirements, designs, security goals, targets, ...

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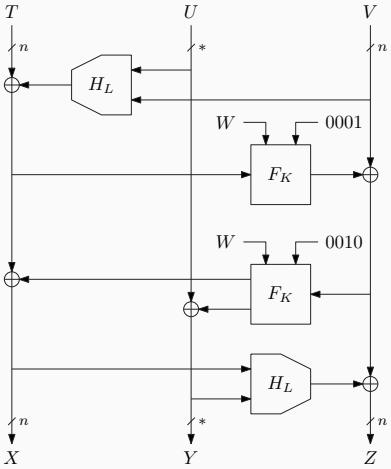
This work: our suggested instantiation of docked double decker

Docked Double Decker

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 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 secure up to approximately

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

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Implications

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

Application to Disk Encryption on SSDs

- Docked double decker is very suitable for disk encryption
  - Disks are separated in sectors
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- Sectors in SSDs have a limited lifetime
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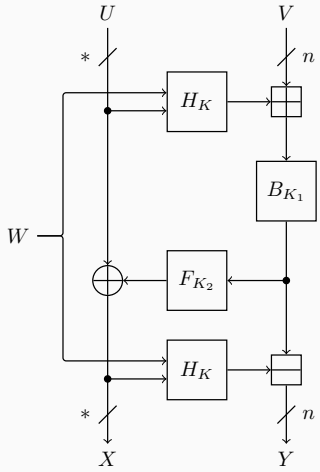
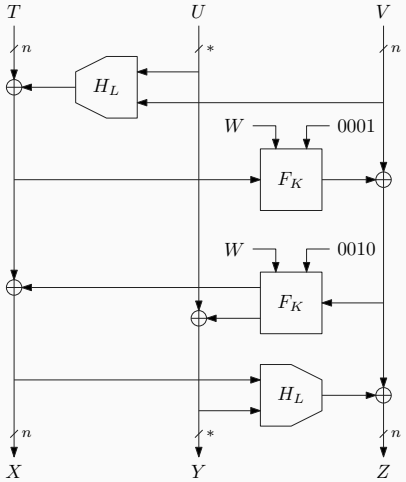
- The Kingston UV500 960 GB has $N = 2^{28}$ sectors, where every sector can be written at most ≈ 500 times
  - Without tweak separation, secure when $2\binom{500N}{2}\epsilon \approx 2^{74}\epsilon \ll 1$
  - With tweak separation this improves to $2N\binom{500}{2}\epsilon \approx 2^{46}\epsilon \ll 1$

Comparison with Adiantum



Adiantum [CB18]



Docked double decker [GDM19]

Efficient Instantiation

Our Goals and Hurdles to Overcome

Goals

- Instantiation using components as used in NIST standardized schemes:
  - AES [DR02, DR20]
  - Operations in binary extension fields, e.g., as in GHASH [MV04]

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Hurdles

- AES is not a tweakable blockcipher
- AES is rather small (circular reasoning?)
- AES in typical stream cipher modes only gives birthday bound security

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 $(I_1, I_2, \ldots, I_s)$:

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

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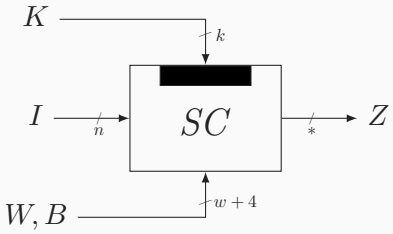
- $Polyval$ is ϵ-XOR-universal with $\epsilon = m_{\max}/2^{128}$ [GLL17]

Recall Goal



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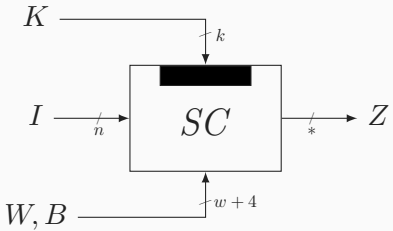

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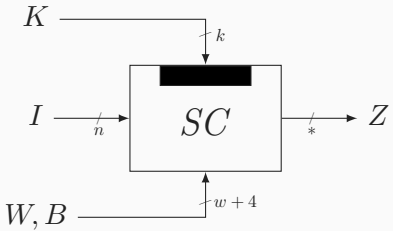
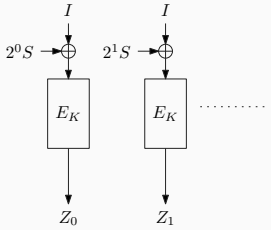


- Construction should be built on top of AES
- We give one construction with birthday bound security
  one construction with beyond birthday bound security

XE-style [Rog04] Tweakable Blockcipher in Counter Mode

- Let $S = E_K(B\|W)$



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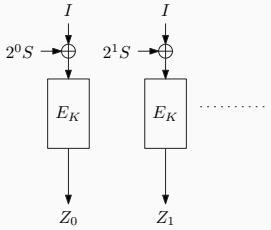

- Stream cipher (and thus $ddd\text{-}AES$) is $2^{n/2}$ PRF-secure

Bonus: Extension $ddd\text{-}AES^{+}$ to Accommodate Variable-Length Tweaks

- $ddd\text{-}AES$ almost seamlessly fits NIST's accordion idea
- Only thing missing: variable-length tweaks

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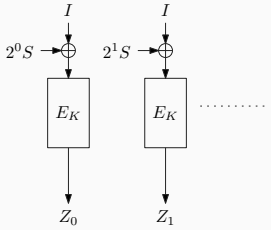
- Pad B, W into $(W_0, W_1, \ldots, W_{l-1} \| B' \| 0^*)$ with $B' = B \oplus 1000$
- Let $S = E_K(W_0 \| 0) \oplus E_K(W_1 \| 1) \oplus \cdots \oplus E_K(W_{l-1} \| B' \| 0^* \| (l-1))$



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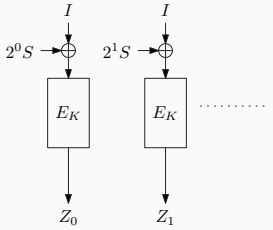

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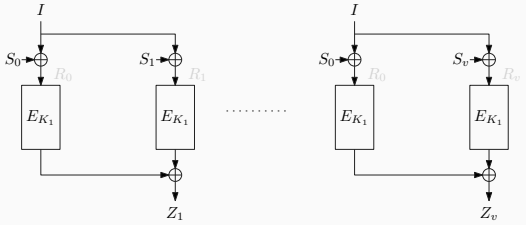
$\widetilde{XORP}$ PRF in Counter Mode

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



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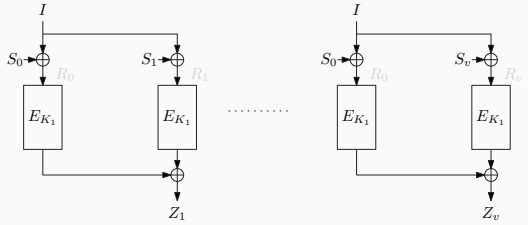
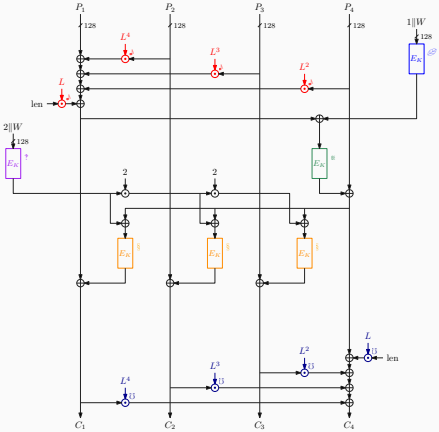
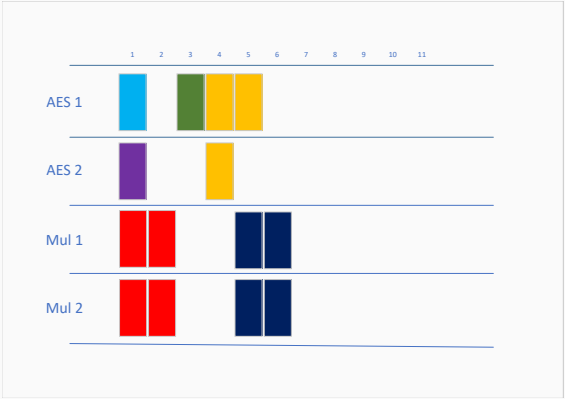


- Corresponding stream cipher runs $\widetilde{XORP}$ in counter mode
- Stream cipher (and thus $bbb\text{-}ddd\text{-}AES$) is $2^{2n/3}$ PRF-secure when tweaks are not used too often

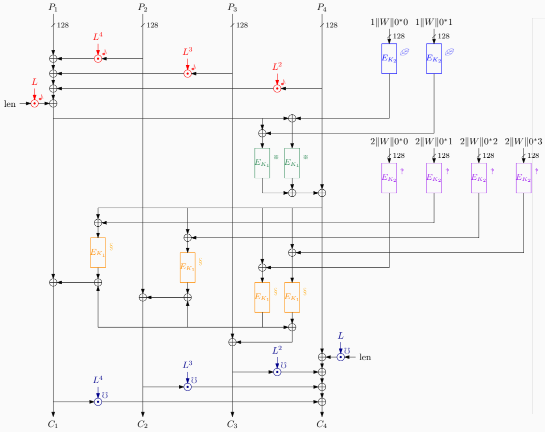
Efficiency

Implementation Design of $ddd\text{-}AES$ (512-Bit Message)

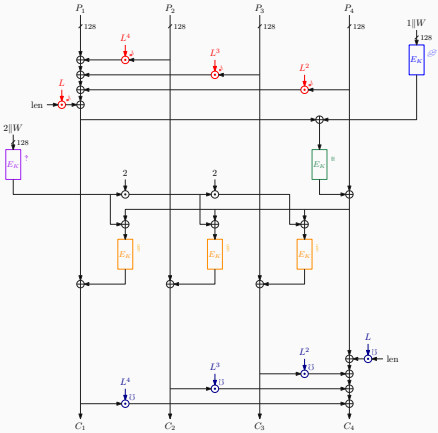




Implementation Design of *bbb-ddd-AES* (512-Bit Message)



Implementation Design of $ddd\text{-}AES$ (1024-Bit Message)



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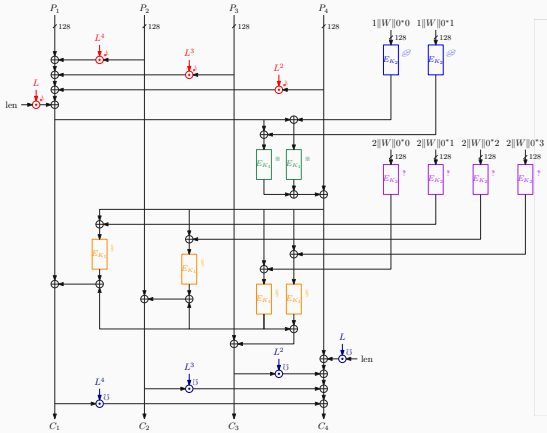

Benchmarks

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- $ddd\text{-}AES$ and $bbb\text{-}ddd\text{-}AES$ on an Intel® Core™ i7-10610U
- C implementation using AES-NI and PCLMULQDQ

Message length (bytes)	32	48	64	96	128	256	512	1024	2048
$ddd\text{-}AES$ x1	6	4.3	3.4	2.8	2.5	2.3	2.2	2.1	2.1
$ddd\text{-}AES$ x2	6	3.9	3.2	2.5	2.0	1.7	1.5	1.3	1.3
$ddd\text{-}AES$ x3	9	4.6	3.1	2.5	2.1	1.4	1.2	1.1	1.0
$ddd\text{-}AES$ x4	7	4.3	3.5	2.6	2.3	1.6	1.3	1.1	1.0
$ddd\text{-}AES$ x5	8	4.6	3.8	2.4	2.2	1.5	1.2	1.1	1.0
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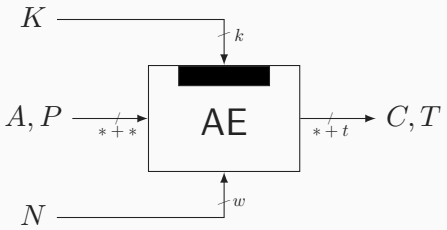
- For comparison, CBC encryption takes ≈ 1.4 cpb for 2048 byte messages

Application to Authenticated Encryption

Authenticated Encryption



- Using key K:
  - Plaintext P is encrypted in ciphertext C
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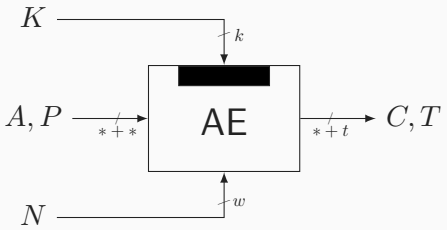

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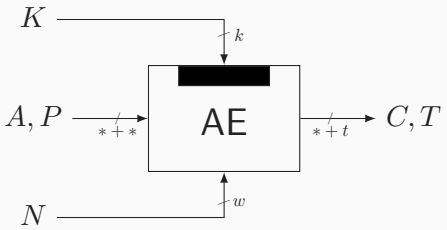

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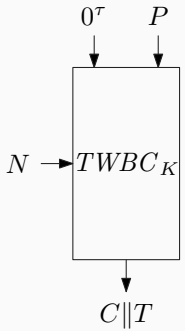
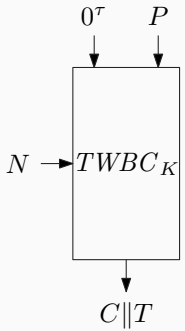
- Decryption outputs message if and only if tag is correct



Robust Authenticated Encryption [HKR15]

- Encryption:
  - Prepend τ zeros to P
  - Evaluate with $TWBC_K$ to obtain $C\|T$
- Decryption:
  - Decrypt $C\|T$ using $TWBC_K^{-1}$
  - If result starts with τ zeros: output P

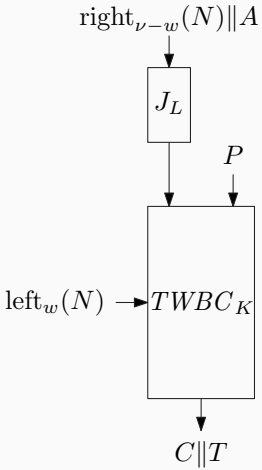


Robust Authenticated Encryption [HKR15]

- Encryption:
  - Prepend τ zeros to P
  - Evaluate with $TWBC_K$ to obtain $C\|T$
- Decryption:
  - Decrypt $C\|T$ using $TWBC_K^{-1}$
  - If result starts with τ zeros: output P

Limitations in Our Context

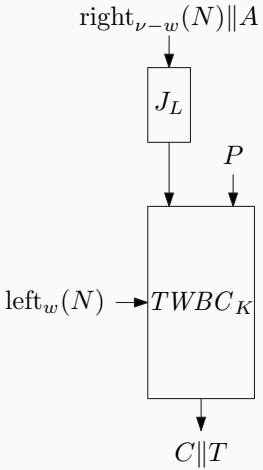
- No associated data (but $ddd\text{-}AES^+$ okay)
- Somewhat small nonce (124 bits for $ddd\text{-}AES$ and 96 bits for $bbb\text{-}ddd\text{-}AES$)



Building Blocks

- $TWBC_K$: tweakable wide blockcipher
- J_L: universal hash

Advanced Authenticated Encryption with Associated Data (aaa)



Building Blocks

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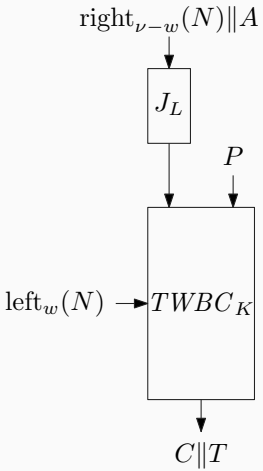
Rationale

- N partially entered into tweak
- Rest of N and A hashed into τ-bit string



Nonce-Respecting Setting

- $\mathrm{left}_w(N)$ unique for each *encryption* query
- Security analysis relies on fact that tweak to $TWBC_K$ is always new

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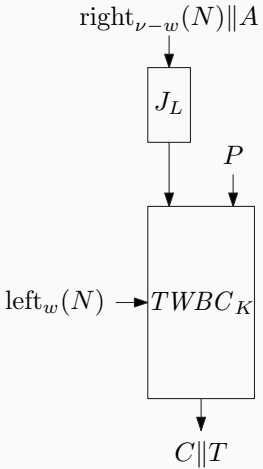

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- N is random for each *encryption* query
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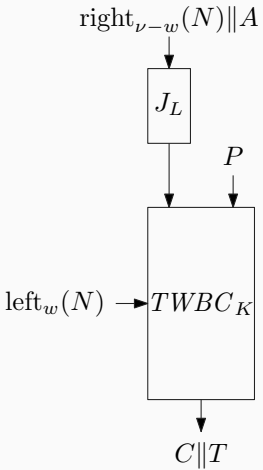

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Nonce-Misusing Setting

- Birthday bound security retained

Conclusion

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Instances of Docked Double Decker

- $ddd\text{-}AES$, $ddd\text{-}AES^{+}$, and $bbb\text{-}ddd\text{-}AES$
- Schemes come with security reduction to AES
- We also introduced authenticated encryption mode aaa for TWBCs
- Paper at `https://eprint.iacr.org/2024/084`

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Future Research

- Turning proposal to context committing ciphers (ccc)
- $\widetilde{XORP}$ is a tweakable blockcipher based PRF used in $bbb\text{-}ddd\text{-}AES$
- Only proven $2n/3$-bit secure under limited tweak-reuse $\rightarrow$ tightness?

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Thank you for your attention!

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