# ZOCB and ZOTR: Tweakable Blockcipher Modes for Authenticated Encryption with Full Absorption

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# Overview: ZOCB and ZOTR

- nonce-based authenticated encryption with associated data (AEAD)
- use a tweakable blockcipher (TBC) as the underlying primitive
- fully utilize the input of the TBC to process a plaintext and associated data (AD)
  - full absorption
  - reduce the number of TBC calls of ΘCB3 and $\mathbb{OTR}$
- have a unique design feature that an authentication tag is independent of a part of AD

# Outline

- Background
- ZOCB and ZOTR
- Instantiation and implementation
  - TAES, a TBC based on AES-256
- Conclusions

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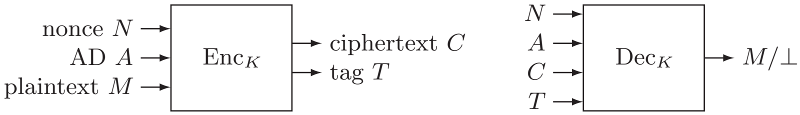
# AEAD

- nonce-based authenticated encryption with associated data (AEAD)
  - privacy and authenticity of plaintexts
  - authenticity of associated data (AD)




- various design approaches
  - dedicated design
  - blockcipher
  - tweakable blockcipher (TBC)
  - cryptographic permutation
  - pseudorandom function

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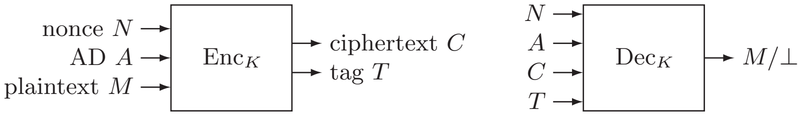


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  - ▷ tweakable blockcipher (TBC)
  - cryptographic permutation
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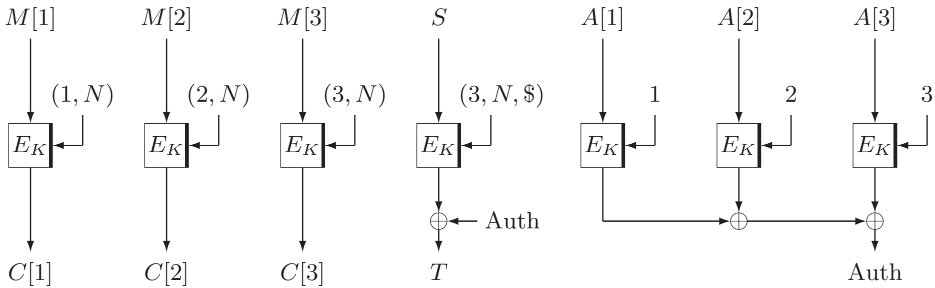
# ΘCB3

- AEAD scheme based on a TBC [KR11]
- was not proposed as a standalone AEAD mode of TBCs, but was introduced as an abstraction of OCB3 for a security proof
- employed in many proposals for its strong features
  - strong provable security result
  - fully parallelizable

[KR11] Ted Krovetz and Phillip Rogaway. The Software Performance of Authenticated- Encryption Modes. FSE 2011

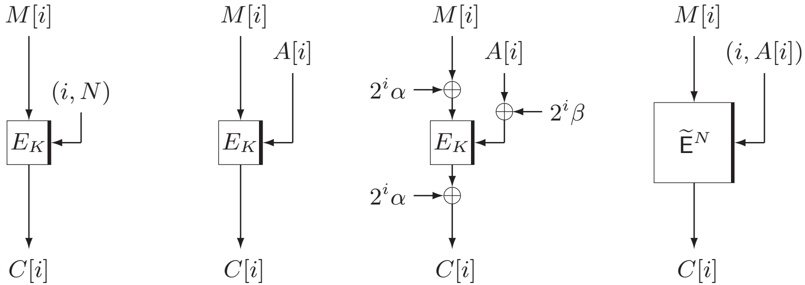
# ΘCB3




- $E_K$ is a TBC, and $S$ is the checksum of $M$
- The process for $M$ and that for $A$ are separated. Can we efficiently integrate these processes?
  - explored for sponge-based [SY15, MRV15] and PRF-based AEAD schemes [RVV15]

[SY15] Yu Sasaki and Kan Yasuda. How to Incorporate Associated Data in Sponge- Based Authenticated Encryption. CT-RSA 2015
[MRV15] Bart Mennink, Reza Reyhanitabar, and Damian Vizár. Security of Full-State Keyed Sponge and Duplex: Applications to Authenticated Encryption. ASIACRYPT 2015
[RVV15] Reza Reyhanitabar, Serge Vaudenay, and Damian Vizár. Boosting OMD for Almost Free Authentication of Associated Data. FSE 2015

# Idea



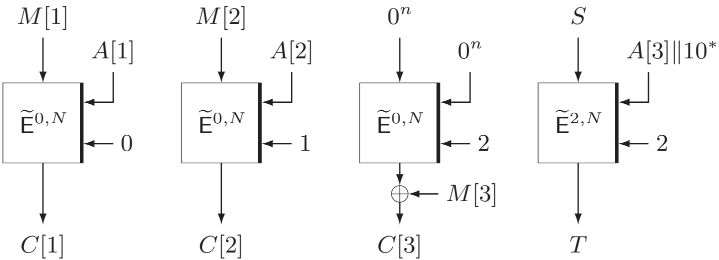

- use the tweak input to process $A[i]$ to fully utilize the input, "full absorption"
- rely on masks for the counter and nonce [Rog04, MI15, IMPS17], $\alpha = E_K^{3,0}(N), \beta = E_K^{3,1}(N)$


[Rog04] Phillip Rogaway. Efficient Instantiations of Tweakable Blockciphers and Refinements to Modes OCB and PMAC. ASIACRYPT 2004

[MI15] Kazuhiko Minematsu and Tetsu Iwata. Tweak-Length Extension for Tweakable Blockciphers. IMACC 2015

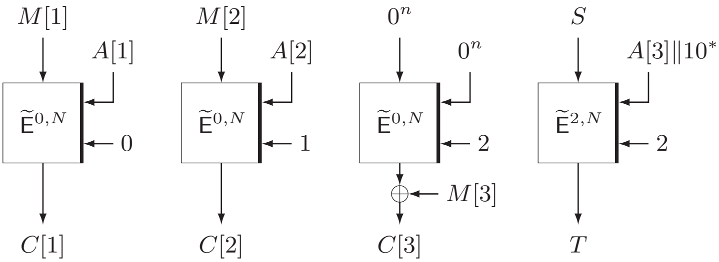
[IMPS17] Tetsu Iwata, Kazuhiko Minematsu, Thomas Peyrin, and Yannick Seurin. ZMAC: A Fast Tweakable Block Cipher Mode for Highly Secure Message Authentication. CRYPTO 2017

# From ΘCB3 to iZOCB




- $|M| = 3n, |M[i]| = n, 2n < |A| < 3n, |A[1]| = |A[2]| = n$
- $S = M[1] \oplus M[2] \oplus M[3]$
- (many details are omitted)

# Secure?




- Privacy is fine, from the uniqueness of the nonce and counter
- For authenticity, $S = M[1] \oplus M[2] \oplus M[3]$, $T$ is independent of $A[1]$ and $A[2]$
  - does not seem to provide authenticity...

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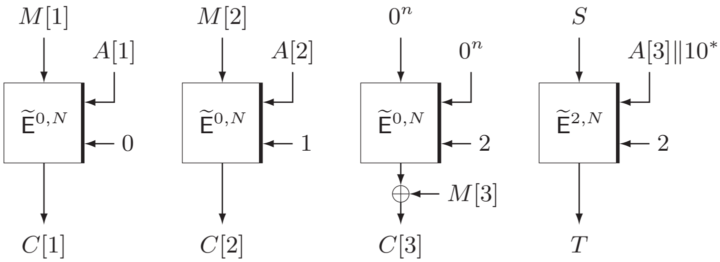


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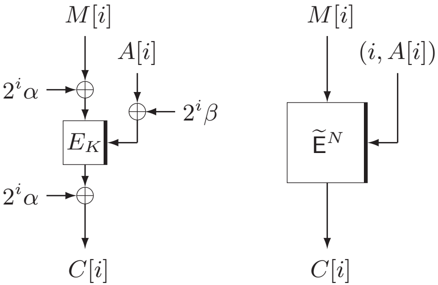
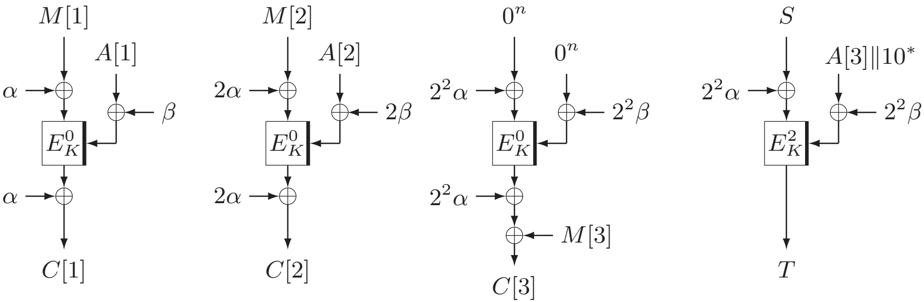
- For authenticity, $S = M[1] \oplus M[2] \oplus M[3]$, $T$ is independent of $A[1]$ and $A[2]$
  - does not seem to provide authenticity...
  - when we decrypt $(N, A, C, T)$, the computed tag from $(N, A, C)$ that is compared with $T$, depends on the entire AD
  - works!

# From iZOCB to ZOCB




- ZOCB is obtained from iZOCB by instantiating $\widetilde{\mathsf{E}}$ with a TBC $E$

# From iZOCB to ZOCB




- $|M| = 3n, |M[i]| = n, 2n < |A| < 3n, |A[1]| = |A[2]| = n$
- $\alpha = E_K^{3,0}(N), \beta = E_K^{3,1}(N), S = M[1] \oplus M[2] \oplus M[3]$
- If AD is not long, there is no separate process for AD, and the process of AD is fully integrated into the process of a plaintext
- If AD is long, there is a separate process for it

# Provable Security Results

- standard security notions of nonce-based AEAD schemes [Rog02]
  - privacy: indistinguishability from random bits under CPA
  - authenticity: unforgeability under CCA
  - nonce-respecting adversaries
  - $E_K : \{0,1\}^t \times \{0,1\}^n \to \{0,1\}^n$
- $\mathbf{Adv}^{\mathrm{priv}}_{\mathrm{ZOCB}[\mathrm{Perm}(\mathcal{W},n)]}(\mathcal{A}) \leq 4\sigma^2_{\mathrm{priv}}/2^{n+\min\{n,t\}}$
- $\mathbf{Adv}^{\mathrm{auth}}_{\mathrm{ZOCB}[\mathrm{Perm}(\mathcal{W},n)]}(\mathcal{A}) \leq 4\sigma^2_{\mathrm{auth}}/2^{n+\min\{n,t\}} + 4q'/2^n$
- ZOCB has the full $n$-bit security when $t \geq n$

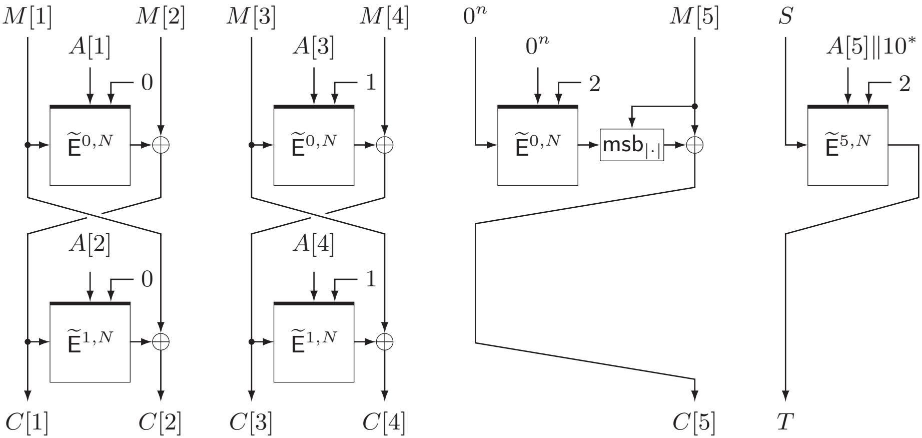
[Rog02] Phillip Rogaway. Authenticated-Encryption with Associated-Data. ACM CCS 2002

# ZOTR

- OTR is an AEAD scheme based on a blockcipher with all the features of OCB3, without using decryption of the blockcipher [Min14]
  - provable security, full parallelizability
- makes use of two round Feistel network
- $\mathbb{OTR}$ is the TBC-based counterpart
  - has a separate process of AD
  - makes the same number of TBC calls as ΘCB3
  - we can integrate the process of AD into that of a plaintext

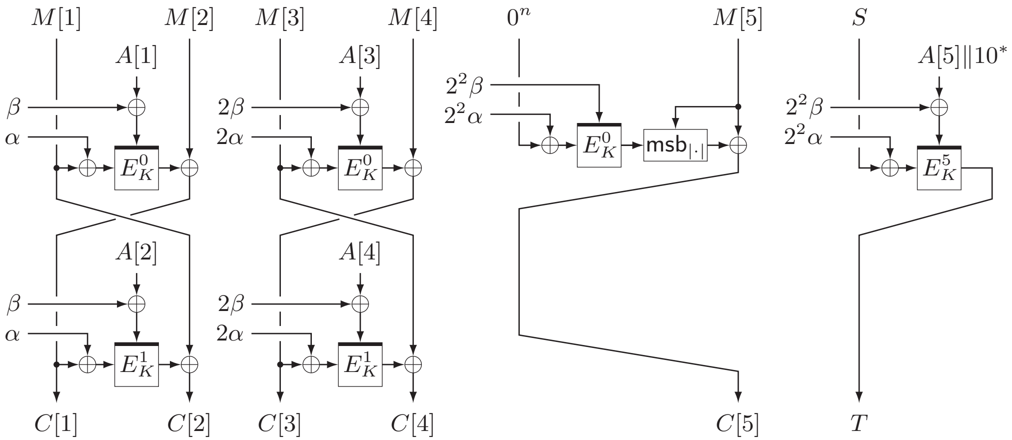
[Min14] Kazuhiko Minematsu. Parallelizable Rate-1 Authenticated Encryption from Pseudorandom Functions. EUROCRYPT 2014

# From $\mathbb{OTR}$ to iZOTR




- The process of AD is integrated into the process of a plaintext

# From iZOTR to ZOTR




- ZOTR is obtained from iZOTR by instantiating $\widetilde{\mathrm{E}}$ with $E$
  - slightly simpler than the case of ZOCB, since the decryption of $E$ is not involved

# Provable Security Results

- standard security notions of nonce-based AEAD schemes [Rog02]
  - $E_K : \{0,1\}^t \times \{0,1\}^n \to \{0,1\}^n$
- $\mathbf{Adv}^{\mathrm{priv}}_{\mathrm{ZOTR}[\mathrm{Perm}(\mathcal{W},n)]}(\mathcal{A}) \leq 4\sigma^2_{\mathrm{priv}}/2^{n+\min\{n,t\}}$
- $\mathbf{Adv}^{\mathrm{auth}}_{\mathrm{ZOTR}[\mathrm{Perm}(\mathcal{W},n)]}(\mathcal{A}) \leq 4\sigma^2_{\mathrm{auth}}/2^{n+\min\{n,t\}} + 6q'/2^n$
- ZOTR also has the full $n$-bit security when $t \geq n$

[Rog02] Phillip Rogaway. Authenticated-Encryption with Associated-Data. ACM CCS 2002

# Comparison

| Scheme | Prim. | # of calls | | Inv. | Para. | Security | Ref. |
|---|---|---|---|---|---|---|---|
| | | $a < m$ | $a \geq m$ | | | | |
| OCB3 | $n$-BC | $a + m$ | | N | Y | $n/2$ | [KR11] |
| OTR | $n$-BC | $a + m$ | | Y | Y | $n/2$ | [Min14] |
| $\Theta$CB3 | $(n, t)$-TBC | $a + m$ | | N | Y | $n$ | [KR11] |
| $\mathbb{OTR}$ | $(n, t)$-TBC | $a + m$ | | Y | Y | $n$ | [Min14] |
| ZOCB | $(n, t)$-TBC | $m$ | $(a + m)/2$ | N | Y | $\min\{n, (n + t)/2\}$ | Ours |
| ZOTR | $(n, t)$-TBC | $m$ | $(a + m)/2$ | Y | Y | $\min\{n, (n + t)/2\}$ | Ours |

- $n$-BC is a blockcipher, $(n, t)$-TBC is a TBC with $t$-bit tweaks
- # of calls is for $at$-bit AD and $mn$-bit plaintexts ($n = t$), neglecting constant number

[KR11] Ted Krovetz and Phillip Rogaway. The Software Performance of Authenticated- Encryption Modes. FSE 2011
[Min14] Kazuhiko Minematsu. Parallelizable Rate-1 Authenticated Encryption from Pseudorandom Functions. EUROCRYPT 2014

# Cost

- The use of a mask requires a doubling operation
- The tweak does not behave like a counter, and updating the tweak can add a computational cost
- If AD is short, then ZOCB/ZOTR can be slower if the cost for doubling is larger than the efficiency gain
- In order to see the practical efficiency gain, we instantiated and implemented ZOCB and ZOTR

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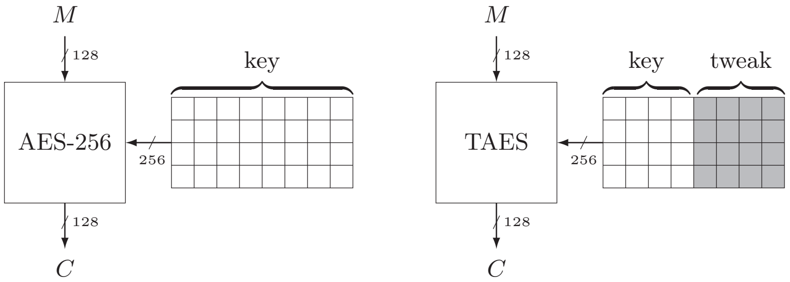
# Instantiation

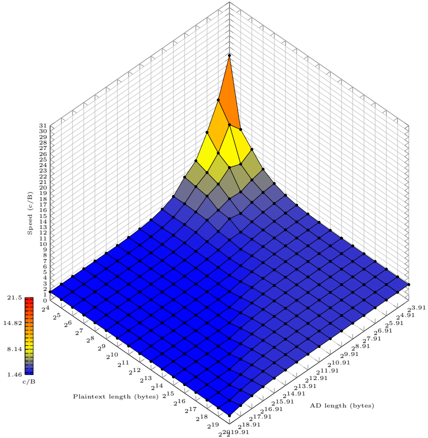
- Tweakable AES, TAES, a 128-bit block, 128-bit key, 128-bit tweak TBC
- obtained from AES-256, where key||tweak is used as the AES-256 key
  - The TAES key is placed in the first part of the AES-256 key (used as the whitening key)
  - We claim 128-bit security of TAES, in the single key setting
    - Related-key attacks in [BK09] cannot be directly applied

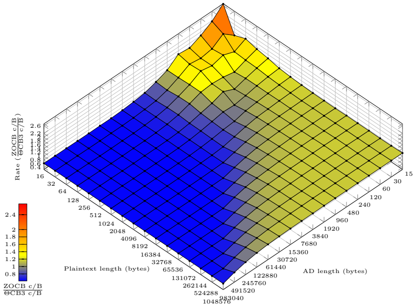



[BK09] Alex Biryukov and Dmitry Khovratovich. Related-Key Cryptanalysis of the Full AES-192 and AES-256. ASIACRYPT 2009

# Implementation

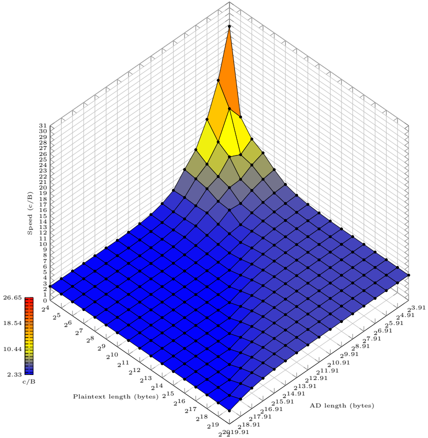
- TAES-$\{\Theta CB3, ZOCB\}$, Intel(R) Core(R) i5-6500 CPU, 3.20 GHz (Skylake family)

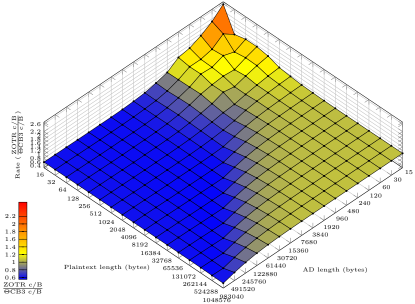


# Implementation

- TAES-$\{\Theta CB3, ZOTR\}$, Intel(R) Xeon(R) E5-2603 v3 CPU, 1.60 GHz (Haswell family)



# Implementation

- We also implemented SKINNY-ZOCB/ZOTR/ΘCB3, where SKINNY-128-256 [BJK+16] is used
- Source code, raw data, and the graphs are available at `https://github.com/zocbzotr`

[BJK+16] Christof Beierle, Jérémy Jean, Stefan Kölbl, Gregor Leander, Amir Moradi, Thomas Peyrin, Yu Sasaki, Pascal Sasdrich, and Siang Meng Sim. The SKINNY Family of Block Ciphers and Its Low-Latency Variant MANTIS. CRYPTO 2016

# Implementation

- For short input data ($|A| \lesssim 480$ bytes or $|A|/|M| \lesssim 0.12$), TAES-ZOCB and TAES-ZOTR are not (always) as fast as TAES-ΘCB3
- For long input data ($|A| \gtrsim 480$ bytes and $|A|/|M| \gtrsim 0.12$), TAES-ZOCB and TAES-ZOTR perform better than TAES-ΘCB3
- Asymptotically with long data ($|A|/|M| \gtrsim 0.12$), the performance gain of TAES-ZOCB/ZOTR is about 40%, they are about $1.7\times$ faster than TAES-ΘCB3
- Similar observations hold for SKINNY-ZOCB/ZOTR/ΘCB3

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  - reduce the number of TBC calls of ΘCB3 and $\mathbb{OTR}$
- provable security results
- software implementation results
- Future directions/open questions
  - designing a TBC with large tweak space with efficient tweak update
  - detailed security analysis of TAES
  - apply the design approach of ZOCB/ZOTR to other TBC-based constructions
    - tweakable enciphering schemes
    - robust AE schemes
    - online AE schemes

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Thank you!