Reconsidering the Security Bound of AES-GCM-SIV

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Summary of the contribution

- we reconsider the security of the AEAD scheme AES-GCM-SIV designed by Gueron, Langley, and Lindell
- we identify flaws in the designers' security analysis and propose a new security proof
- our findings leads to significantly reduced security claims, especially for long messages
- we propose a simple modification to the scheme (key derivation function) improving security without efficiency loss

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  - widely deployed, not nonce-misuse resistant [Jou06, BZD+16]
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- AES-GCM-SIV [GLL16, GLL17]
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  - similar to GCM-SIV but three modifications:
    - universal hash function (POLYVAL instead of GHASH)
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Nonce-Based Authenticated Encryption (nAE)

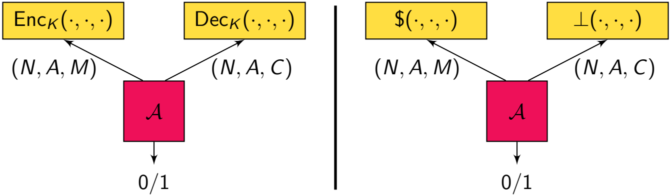
Syntax

A nAE scheme Π is a pair of algorithms $(\Pi.\mathrm{Enc}, \Pi.\mathrm{Dec})$ where

- algorithm $\Pi.\mathrm{Enc}$ takes
  - (a key K)
  - a nonce N
  - associated data A
  - a message M

  and returns a ciphertext C.
- algorithm $\Pi.\mathrm{Dec}$ takes K and (N, A, C) and returns M or $\perp$.

Nonce-Based Authenticated Encryption (nAE)



Security (all-in-one definition)

- The scheme Π is secure if adversary $\mathcal{A}$ cannot distinguish $(\mathrm{Enc}_K, \mathrm{Dec}_K)$ and $(\$, \perp)$.
- $\mathcal{A}$ cannot ask a decryption query (N, A, C) if it received C from an encryption query (N, A, M)
- $\mathcal{A}$ is said nonce-respecting if it never repeats a nonce in encryption queries.

Misuse-Resistant AE (MRAE)

Nonce-misuse resistance (informal) [RS06]

A nAE scheme is said nonce-misuse resistant if repeating a nonce in encryption queries:

- does not harm authenticity
- hurts confidentiality only insofar as repetitions of triplets (N, A, M) are detectable

- $\simeq$ deterministic authenticated encryption
- MRAE schemes *cannot* be online (each ciphertext bit must depend on each input bit)

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SIV composition method

- SIV (*Synthetic IV*) [RS06] combines a PRF $F_{K_1}(N, A, M)$ and an IV-based encryption scheme $\Pi.\mathrm{Enc}_{K_2}(IV, M)$
- provides nonce-misuse resistance: any change to N, A, or M randomly modifies the tag and C

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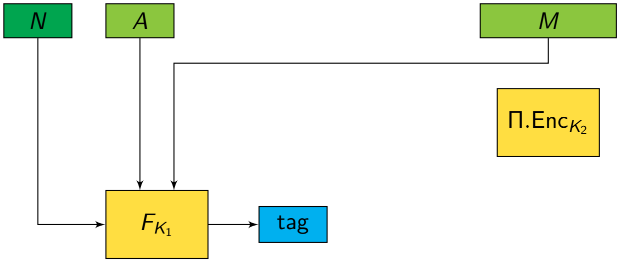

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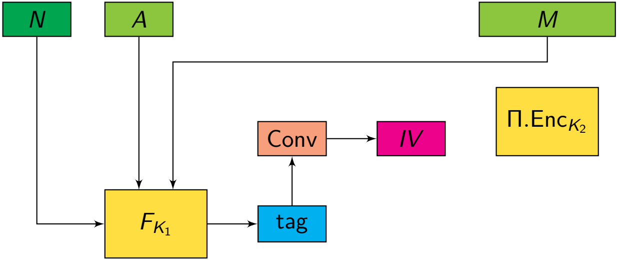

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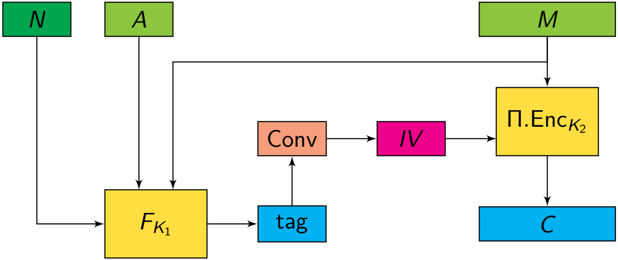

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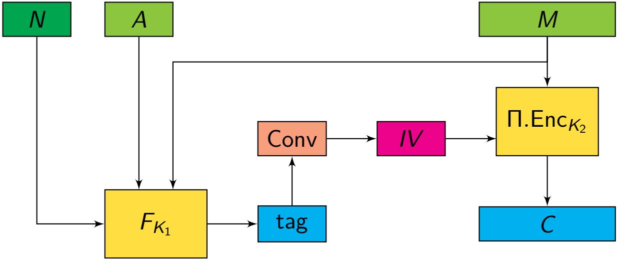

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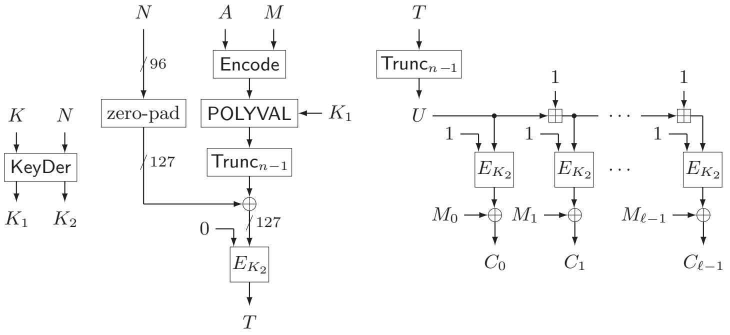
Details of AES-GCM-SIV



- AES-GCM-SIV = KeyDer + GCM-SIV$^+$
- same BC key K_2 used in MAC and encryption
  $\Rightarrow$ 0/1 domain separation

Outline

Background on AES-GCM-SIV

Fixing the Security Bound

Improving Key Derivation

Final Remarks

Designers' claims ([GLL17], Theorem 6)

$$\mathbf{Adv}^{\text{mrae}}_{\text{AES-GCM-SIV}}(\mathcal{A}) \leq \underbrace{\mathbf{Adv}^{\text{prp}}_{\text{AES}}(\mathcal{A}'') + \min\left\{\frac{36Q^2}{2^{129}}, \frac{6Q}{2^{96}}\right\}}_{\text{KeyDer PRF-security}}$$

$$+ Q \underbrace{\left(2\mathbf{Adv}^{\text{prf}}_{\text{AES}}(\mathcal{A}') + \frac{R^2 \ell_M}{2^{126}} + \frac{R^2 + 2q_D}{2^{127}}\right)}_{\text{GCM-SIV}^+ \text{ MRAE-security}},$$

- ℓ_M = maximal message length of encryption queries
- Q = maximal number of distinct nonces in encryption queries
- R = maximal number of nonce repetitions in encryption queries
- q_D = number of decryption queries per nonce, σ_D = total length
- $\mathcal{A}'$ makes at most $Q(2R + 2q_D + \sigma_D)$ queries
- $\mathcal{A}''$ makes at most $6Q$ queries

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Problems in designers' bound

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- mixes PRP- and PRF-security of the underlying BC
- AD's length not taken into account
- number of queries $Q(2R + 2q_D + \sigma_D)$ of $\mathcal{A}'$ is flawed
- $Q = 0$ (no encryption queries), $q_D > 0 \Rightarrow \mathbf{Adv}^{\mathrm{mrae}}_{\text{AES-GCM-SIV}}(\mathcal{A}) = 0$
  $\rightarrow$ impossible for MRAE security definition
  (non-zero probability to forge a tag randomly)

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Main changes:

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- $\mathcal{A}'$ makes $R\ell_M$ queries versus $2QR$ in [GLL17]

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Dominating term

$$\mathbf{Adv}^{\mathsf{mrae}}_{\mathsf{AES\text{-}GCM\text{-}SIV}}(\mathcal{A}) \leq \mathbf{Adv}^{\mathsf{prp}}_{\mathsf{AES}}(\mathcal{A}'') + \min\left\{\frac{36Q^2}{2^{129}}, \frac{6Q}{2^{96}}\right\} + Q\mathbf{Adv}^{\mathsf{prf}}_{\mathsf{AES}}(\mathcal{A}') + \frac{QR^2\ell_M}{2^{126}} + \frac{QR^2\ell_A}{2^{128}},$$

- [GLL17] claimed the security bound is dominated by $\frac{QR^2\ell_M}{2^{126}}$ (accounts for counter collision)
- but in fact the PRF term is $\sim \ell_M$ larger ($\mathcal{A}'$ makes $R\ell_M$ queries)

$$Q\mathbf{Adv}^{\mathsf{prf}}_{\mathsf{AES}}(\mathcal{A}') \simeq Q\mathbf{Adv}^{\mathsf{prp}}_{\mathsf{AES}}(\mathcal{A}') + \frac{QR^2\ell_M^2}{2^{129}}$$

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Concrete security claims

Scheme	N_E	Q	R	ℓ_M	our bound	[GLL17] claim
AES-GCM-SIV (nonce based)	2^{32}	2^{32}	1	2^{32}	2^{-33}	2^{-61}
	2^{64}	2^{64}	1	2^{32}	2^{-1}	2^{-29}
	2^{31}	1	2^{31}	2^{32}	2^{-3}	2^{-32}
	2^{31}	1	2^{31}	2^{16}	2^{-35}	2^{-48}
	2^{39}	1	2^{39}	2^{16}	2^{-19}	2^{-32}
	2^{42}	1	2^{42}	2^{10}	2^{-25}	2^{-32}
	2^{50}	2^{42}	2^{8}	2^{32}	2^{-7}	2^{-36}
	2^{50}	2^{42}	2^{8}	2^{16}	2^{-39}	2^{-51}
	2^{50}	2^{46}	2^{4}	2^{32}	2^{-11}	2^{-40}
AES-GCM-SIV (random IV)	2^{48}	—	—	2^{32}	2^{-14}	2^{-44}
	2^{63}	—	—	2^{16}	2^{-31}	2^{-32}

$N_E = QR =$ total number of encryption queries

Taking decryption queries into account

- the adversary can choose nonces freely in decryption queries (it could reuse the same nonce q_D times)
- naive bound ($Q + q_D$ distinct nonces)

$$\mathbf{Adv}^{\mathrm{mrae}}_{\text{AES-GCM-SIV}}(\mathcal{A}) \leq (Q + q_D) \underbrace{\left((\cdots) + \frac{(R + q_D)^2(\ell_M + \ell_A)}{2^n} \right)}_{\text{GCM-SIV}^+ \text{ security}}$$

- loose bound (cubic in q_D)
- with a more careful multi-user analysis we recover a bound quadratic in q_D

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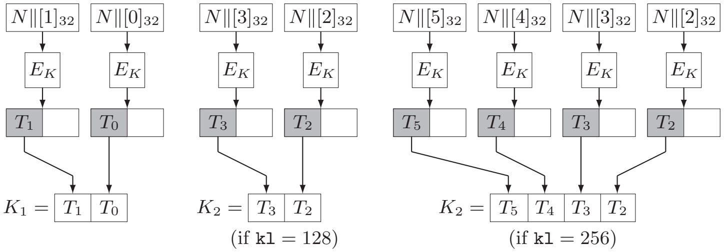
Outline

Key Derivation Function

- $(K, N) \xrightarrow{\text{KeyDer}} (K_1, K_2)$ constructed from E
- standard PRP-to-PRF conversion problem
- based on truncation [HWKS98, GGM18]



A Better Key Derivation Function

- security of truncation when dropping m bits: for q large enough,

$$\mathbf{Adv}^{\mathrm{prf}}_{\mathrm{Trunc}_{n-m}[P]}(q) \leq \frac{q}{2^{(m+n)/2}}$$

- when dropping $m = n/2$ bits:
  - two BC calls to obtain an n-bit key
  - security up to $2^{3n/4}$ queries
- better construction: XOR of permutations

$$K_1 = E_K(N \| [0]_{32}) \oplus E_K(N \| [1]_{32})$$

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Concurrent/Subsequent work

- Gueron and Lindell, *Better Bounds for Block Cipher Modes of Operation via Nonce-Based Key Derivation*, CCS 2017
  - security definition puts an upper bound on the number of decryption queries per nonce
    → complicated to enforce in practice (stateful decryption)
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  - shows that the security of AES-GCM-SIV does not degrade in the multi-user setting

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The end...

Thanks for your attention!

Comments or questions?

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