Romulus as NIST LWC Finalist

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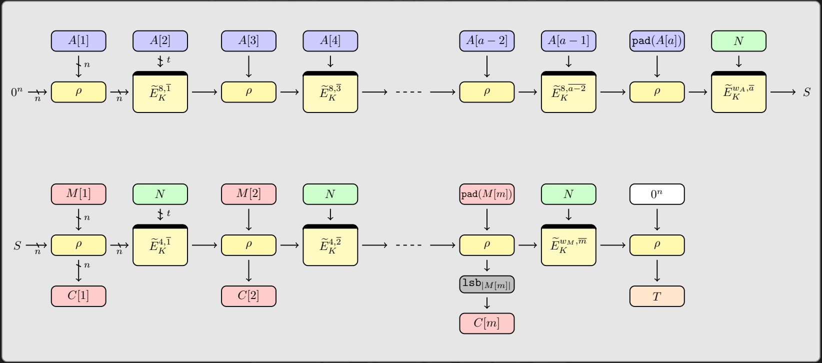
Romulus **versions**

Version	**Mode**	**Primitive**	**Comment**
Romulus-N	Romulus-N1	SKINNY-128/384+	BBB nonce-respecting AEAD
Romulus-M	Romulus-M1		BBB nonce-misuse resistant + RUP AEAD
Romulus-T	TEDT		Leakage res. AEAD (CIML2 + CCAmL2)
Romulus-H	MDPH		Hash function

All our versions provide $\sim$ **128-bit security** - time and data
(in contrary to many remaining candidates)

Romulus-N/Romulus-M security proofs are in the **standard model**
(in contrary to all remaining candidates except GIFT-COFB)

Romulus-N : BBB nonce-respecting AEAD

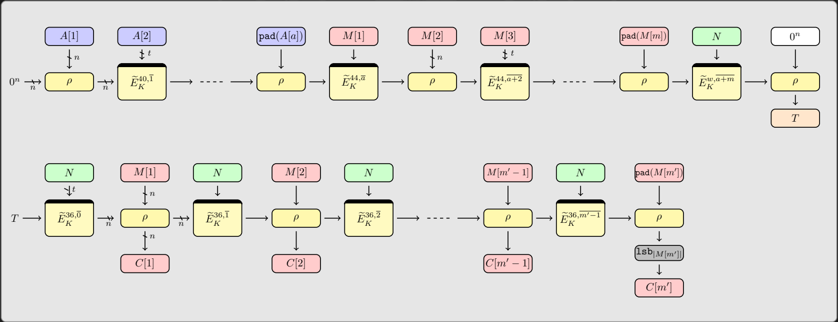


Provides **BBB 128-bit security** - data and time

(in contrary to many remaining candidates)

New : Provides **nonce-misuse resilience**

Romulus-M : BBB nonce-misuse resistant AEAD



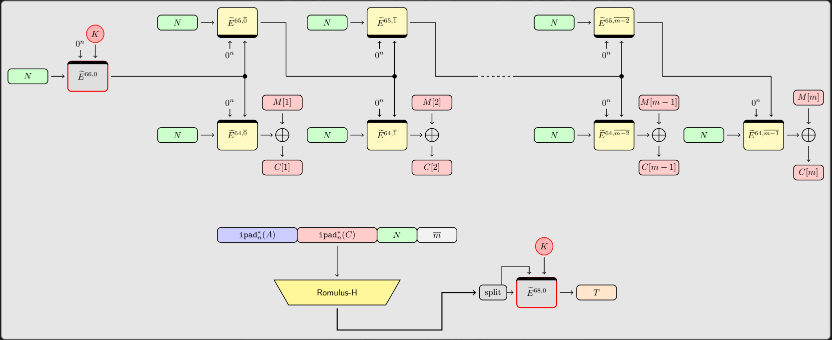
Provides **nonce-misuse resistance** (strong MRAE notion)

(in contrary to all remaining candidates)

Provides **Release of Unverified Plaintext** security (INT-RUP + PA1)

(in contrary to all remaining candidates except ELEPHANT)

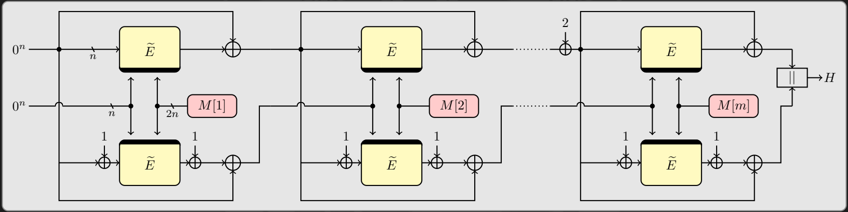
Romulus-T : Leakage resilient AEAD



Provides **CIML2** (best for integrity) + **CCAmL2** (best for privacy)
(in contrary to all remaining candidates except ISAP)

Provides **nonce-misuse resilience**

Romulus-H : rate 1 Hash function



Indifferentiability up to $n - \log_2 n$

Can easily/efficiently provide **XOF** functionality

Security

Security proofs review by third-party

Confidence in a security proof correctness is very important. Our Romulus-N/Romulus-M proofs have been reviewed and published in ToSC NIST LWC and we continue verifying them, but we also adopted an approach of proof verification through a third-party review.

Third-party analysis of the Romulus-N/Romulus-M operating modes conducted by **Prof. Jooyoung Lee** (KAIST, Korea). The report confirms the correctness of the provable security result by presenting an independent proof with a different proof strategy. Full report here :

https://romulusae.github.io/romulus/docs/Security_evaluation_Romulus_Jooyoung_Lee.pdf

Conclusion. In this evaluation, we proved the security of Romulus-N and Romulus-M; the best attack on any of these modes implies a chosen-plaintext attack (CPA) in the single-key setting against the underlying tweakable block cipher. So unless the tweakable block cipher is broken by CPA adversaries in the single-key setting, Romulus indeed maintains the claimed n-bit security. To evaluate the security of Romulus, with the standard model proof, we can focus on the security evaluation of the underlying primitive. The provable security of Romulus-N and Romulus-M is a clear advantage over any scheme with security proofs in non-standard models.

New Romulus-H proof

Romulus-H is based on the Naito's MDPH construction (basically **Hirose DBL** compression function construction [FSE06] inside a **Merkle-Damgård with Permutation** (MDP) mode [JoC12]).

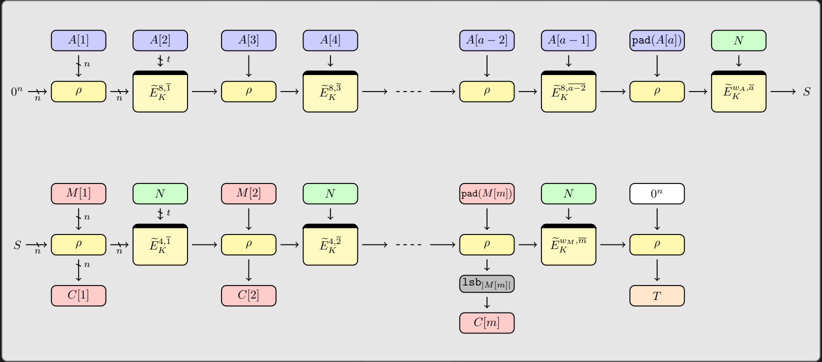
New MDPH and Romulus-H security proof

Previous analysis from Naito's contained a gap (in the definition of the simulator simulating the decryption of the underlying block cipher). We proposed a new MDPH and Romulus-H security proof, **same bounds up to constants -** published at IET Info Sec journal (2022) : `https://eprint.iacr.org/2021/1469.pdf`

New Romulus-N nonce-misuse resilience proof

New nonce-misuse resilience proof for Romulus-N

New nonce-misuse resilience proof for Romulus-N (ongoing work) : perfect for privacy, birthday for authenticity with graceful degradation (wrt nonce repetition).



Why Romulus-M is very well suited for lightweight

For a constrained device, it is difficult :

- to **ensure the non-repetition of a nonce** (counter requires synchronization, storing nonces requires a lot of memory, generating them randomly requires a good/non-buggy randomness source)
- to **retain the result of decryption in secure memory** until the verification result (large secure memory is difficult)

RUP security of Romulus-M

integrity : Romulus-M is INT-RUP secure (both nonce-respecting/misuse)
privacy : Romulus-M is PA1 secure (Plaintext Awarness)

Nonce-misuse resistance of Romulus-M

integrity/privacy : Romulus-M is MRAE secure (up to birthday bound, with graceful degradation with number of nonce repeats).

Romulus-M is the ONLY remaining design to have RUP (except ELEPHANT) and MRAE, for a cost that is slightly more than Romulus-N and almost the same design

SKINNY family of Tweakable Block Ciphers

SKINNY:

- an ultra lightweight Tweakable Block Cipher (TBC) family
- SKINNY is with ASCON probably the most analysed primitive used in the competition (except Keccak, already standard)
- Published as ISO/IEC standard : ISO/IEC 18033-7:2022
- already used in practical applications

C. Beierle, J. Jean, S. Kölbl, G. Leander, A. Moradi,
T. Peyrin, Y. Sasaki, P. Sasdrich and S.M. Sim

CRYPTO 2016

https://sites.google.com/site/skinnycipher/

Current best attacks on SKINNY-128/384 and SKINNY-128/384+

Hadipour *et al.* (ePrint 2020:1317 and FSE 2022) [HBS20] :

- related-key rectangle attacks up to 30 rounds (2^{361} time, 2^{125} data)
- with one TK word fixed (TK2), up to 24 rounds (2^{209} time, 2^{125} data)
- distinguisher on 25 rounds with prob. $2^{-116.6}$ (TK2 : 21 rounds 2^{-114})

Qin *et al.* (ePrint 2021:656 and FSE 2022) [QDW+21] :

- related-key rectangle attacks up to 30 rounds (2^{341} time, 2^{122} data)
- with one TK word fixed (TK2), up to 25 rounds (2^{226} time, 2^{124} data)
- distinguisher on 22 rounds with prob. $2^{-101.5}$ (TK2 : 19 rounds 2^{-117})

Delaune *et al.* (FSE 2022 best paper) [DDV22] :

- related-key boomerang distinguisher on 24 rounds (2^{86} time/data)
- with one TK word fixed (TK2) up to 20 rounds (2^{86} time/data)

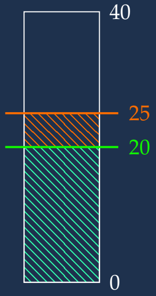
In contrary to many candidates, our internal primitive still have **no distinguisher** (by far).

The security margin of SKINNY-128/384+

A large security margin for SKINNY-128/384+

SKINNY-128/384+ has **40** rounds, proposed by the SKINNY team

- For time/data limited to 2^{128}, current best attack reaches 25 rounds : we maintain a **37% worst case security margin**
- ... and even more if we :
  - restrict to 2^{64} data (probably 1 less round)
  - exclude related-key attacks (probably 4 less rounds)
  - consider the entire Romulus constructions
  - don't allow nonce to repeat
  - actual security margin $\gtrsim$ 50%



SKINNY-128/384+

Performances and Implementations

Software performances of Romulus

Cipher	Uno[1] avg. time [μs]
schwaemm256128v2	1999.740
giftcofb128v1	2250.020
xoodyakround3	2371.040
tinyjambu128v2	2386.180
ascon128v12	2472.060
romulusn1+	2870.170
photonbeetleaead128rate128v1	4821.260
elephant160v1	12477.300
isapa128av20	22486.000
grain128aead	22596.600
aes128k96n	

Cipher	F1[2] avg. time [μs]
xoodyakround3	64.277
schwaemm256128v2	80.914
ascon128v12	81.091
tinyjambu128v2	110.295
giftcofb128v1	131.551
romulusn1+	225.008
grain128aeadv2	241.014
aes128k96n	337.203
photonbeetleaead128rate128v1	590.958
isapa128av20	600.055
elephant160v2	4430.300

Software performance rankings
on AVR (8-bit - left) and ARM Cortex M3 (32-bit - right)
from OTH (Germany) : `lwc.las3.de/table.php`

Hardware performances of Romulus : FPGA

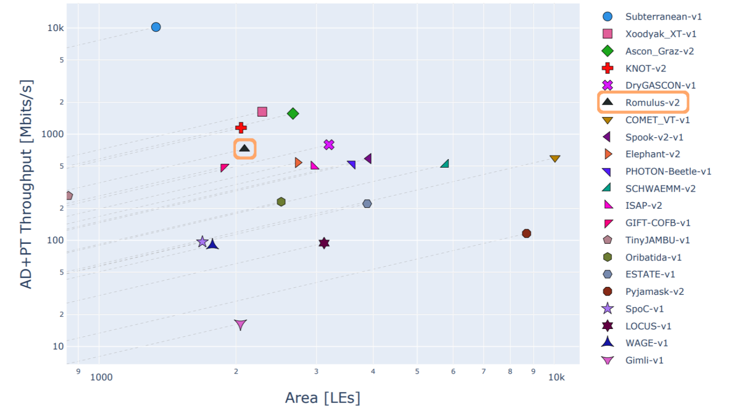
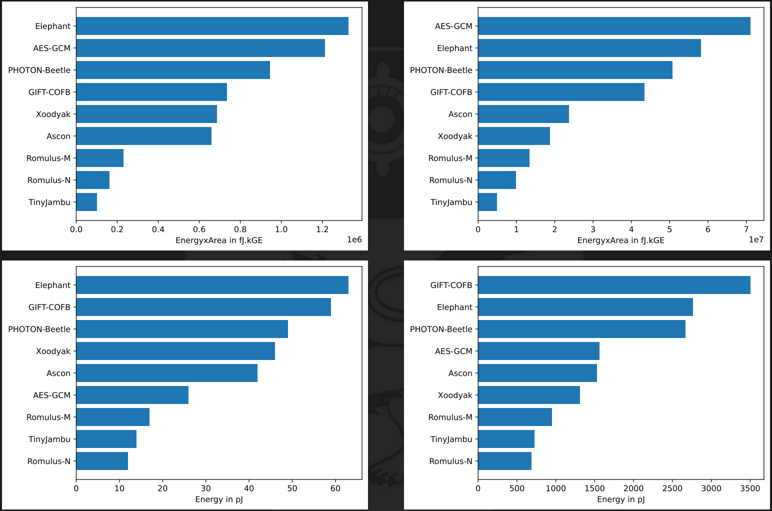


Figure 8: Cyclone-10-LP Encryption AD+PT Throughput for Long Messages vs LEs

FPGA performance from GMU, USA

Hardware performances of Romulus : ASIC



ASIC performance ranking from

`https://github.com/mustafam001/lwc-aead-rtl/`

Threshold implementation of Romulus

Threshold implementation for TBCs

As shown in [Spook,NaitoSS-EC20], TBC are great primitives for thres. impl. compared to BCs or sponges (only n-bit state to be protected)

Enc. of 1600 bytes of A and M using Romulus-N in different implementations.
- stands for unprotected, P for probing, NI, SNI, and C for coupling resistance

Implementation	Cycles	Critical Path(ns)	Throughput (Gbps)	Area (GE)	Goal
Unmasked, 4 rounds/cycle	2318	2	5.52	10124.24	-
Unmasked, 1 round/cycle	6048	1.11	3.81	7348.61	-
Masked, 1 cycle/round	8636	0.65	4.56	33131.25	P
Masked, 2 cycles/round	12088	0.6	2.35	20716.25	P
Masked, 3 cycles/round	18128	0.5	2.82	13276.52	P
Masked, 5 cycles/round	30208	0.5	1.69	14441.25	SNI
Masked, 7 cycles/round	42288	0.5	1.21	16266.52	PINI
Masked, 14 cycles/round	84568	0.5	0.6	15029.7	C

Features

Romulus **features :**

- provably secure in standard model (unlike most LWC candidates)
- full 128-bit security time/data (unlike some LWC candidates)
  Romulus-N priv. bound is 0, auth is $q_d/2^\tau$, doesn't depend on #enc queries (unlike most LWC candidates)
- SKINNY is a stable and well studied primitive, large security margin, no distinguisher (unlike many LWC sponge-based candidates), ISO
- easy nonce-misuse resistance mode (unlike **all** LWC candidates)
  birthday with graceful degradation so ~full security in practice
- no or low overhead for small messages (unlike all LWC sponge-based candidates)
  1 AD and 1 M n-bit blocks need 2 TBC calls with Romulus
- excellent hardware profile, good software profile (good for 4 or 8-bit)
- side-channel protection : efficient masking (small protected state) + Romulus-T mode protection

No TBC currently appears in NIST cryptography standards yet.

The 10 finalists of the ongoing NIST competition

name	type	internal (SECURITY)	distinguisher internal	data. sec. claims	nonce-misuse (CLAIMED FEATURES)	RUP	hash	side-chan. resistance	other
ASCON	perm.	ASCON-p	yes	birthday			✓	some	CAESAR
ELEPHANT	perm.	SPONGENT	no	birthday	integrity	✓			parallel
GIFT-COFB	BC	GIFT	no	birthday					
Grain-128AEAD	SC	Grain	no	full					eSTREAM
ISAP	perm.	ASCON-p	yes	full				yes	
PHOTON-Beetle	perm.	PHOTON	no	full			✓		ISO/IEC
Romulus	TBC	SKINNY	no	full	Romulus-M/T	Romulus-M/T	✓	Romulus-T	ISO/IEC
SPARKLE	perm.	ad-hoc	no	full			✓		
TinyJambu	perm.	ad-hoc	yes	birthday					
Xoodyak	perm.	Xoodoo	yes	full			✓		

Thank you !