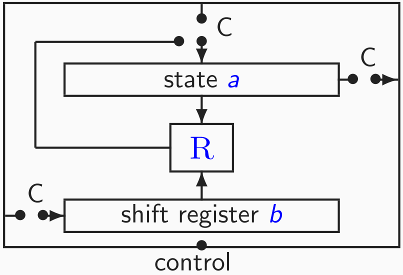
Radbound University

The Subterranean 2.0 Cipher Suite

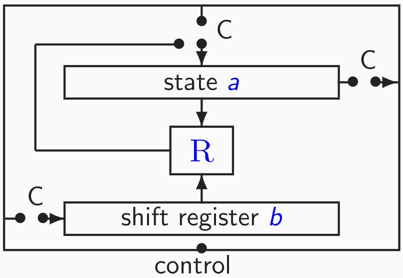
Joan Daemen[1], Pedro Maat Costa Massolino[3], Alireza Mehrdad[1], Yann Rotella[2]
[1]Radboud University NL, [3]PQShield UK, [2]UVSQ, LMV, Université Paris-Saclay FR

Fast Software Encryption Workshop
November 9, 2020

ESCADA


C
C
state a
R
C
shift register b
control

SUBTERRANEAN [JDA 1992]: a stream/hash module



Subhash: $M \rightarrow h$

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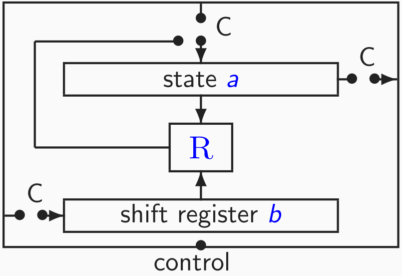

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Substream:	$(K; D)$	$\rightarrow$	Z

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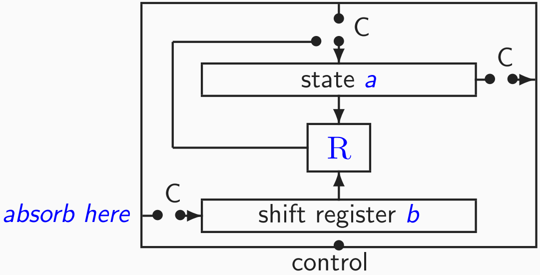

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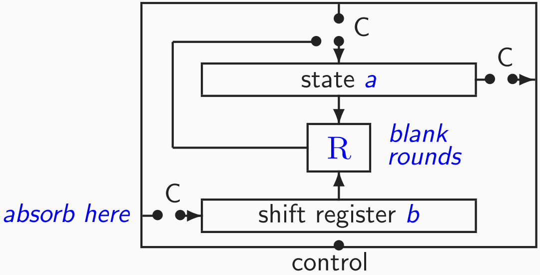

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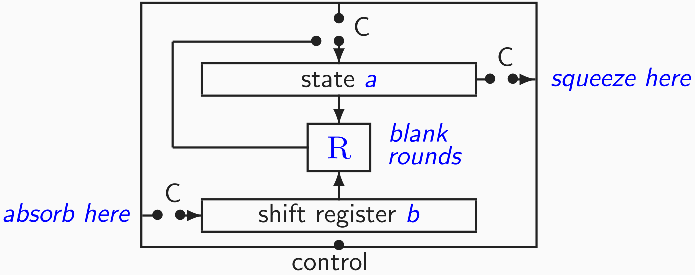

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b: 256-bit shift register with 32-bit stages

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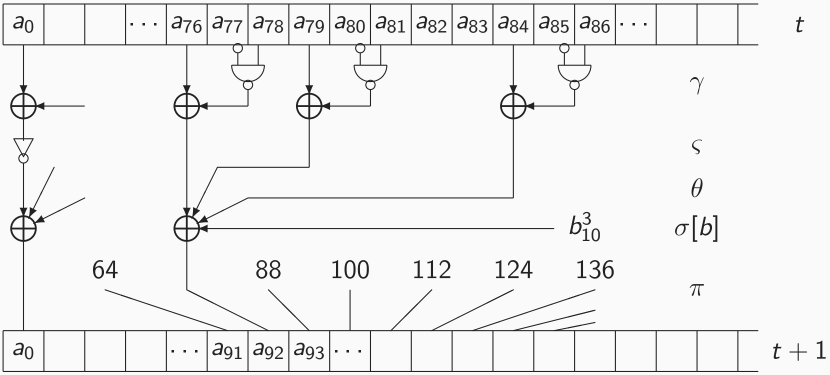
a: 257-bit state: $a \leftarrow \mathrm{R}(a, b)$



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  - but we would go for *low energy* and that implies ASIC anyway
- Low energy?
  - R takes 4 XOR, 1 NAND, 1 NOT per bit and is *shallow*
  - absorbing: 32 bits per round $\rightarrow$ 32 XOR, 8 NAND, 8 NOT per bit
  - squeezing: 16 bits per round $\rightarrow$ 64 XOR, 16 NAND, 16 NOT per bit

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  - absorbing: 32 bits per round $\rightarrow$ 32 XOR, 8 NAND, 8 NOT per bit
  - squeezing: 16 bits per round $\rightarrow$ 64 XOR, 16 NAND, 16 NOT per bit
- Not bad, so let's give it a shot!

Three primitives

XOF: unkeyed hashing with arbitrary-length output & input strings
Deck: keyed function with arbitrary-length output & input strings
SAE: session-supporting nonce-based authentication encryption

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Subterranean 2.0 is Subterranean 1992 refurbished

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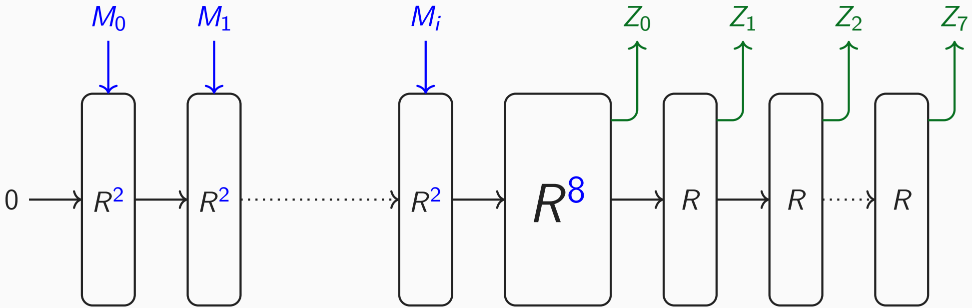
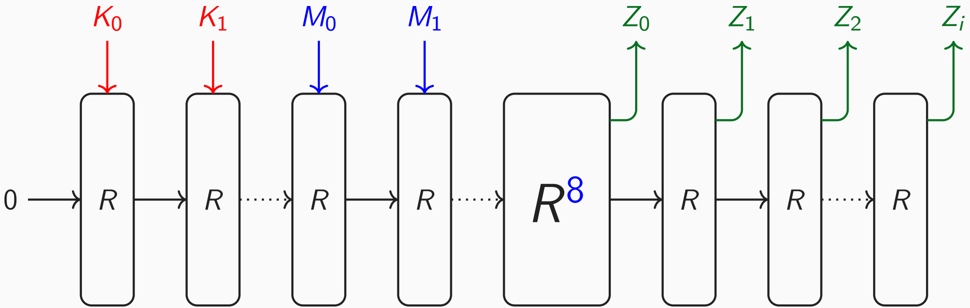
  - 8 *blank* rounds between absorbing and squeezing
  - except for encryption/decryption in SAE that relies on nonce uniqueness

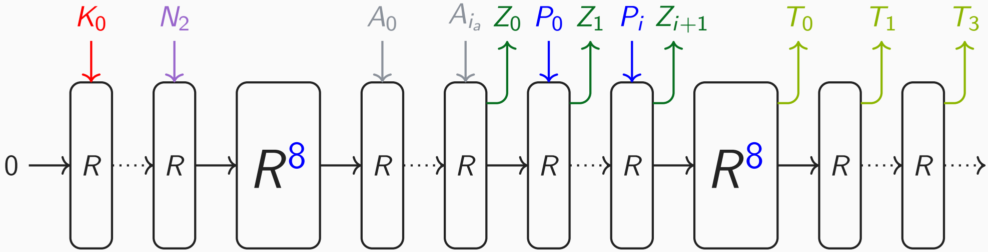
And now to SUBTERRANEAN 2.0 and its rationale in more detail!



- $|M_j|$: **one byte**
- $|Z_j|$: **4 bytes**

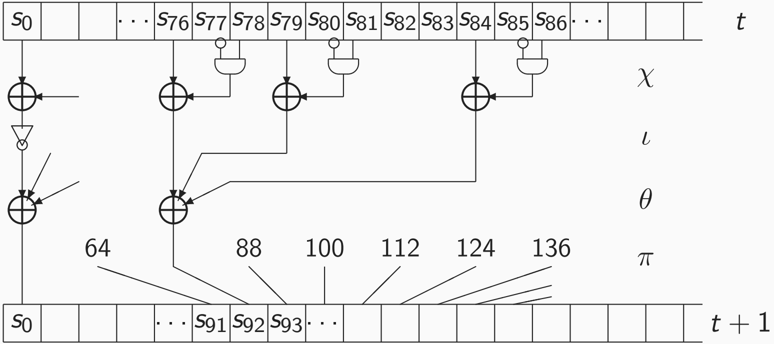


- $|M_j|$, $|Z_j|$, $|K_j|$: **4 bytes**



- $|K_j|$, $|N_j|$, $|A_j|$, $|Z_j|$, $|P_j|$, $|T_j|$: **4 bytes**

The SUBTERRANEAN 2.0 round function



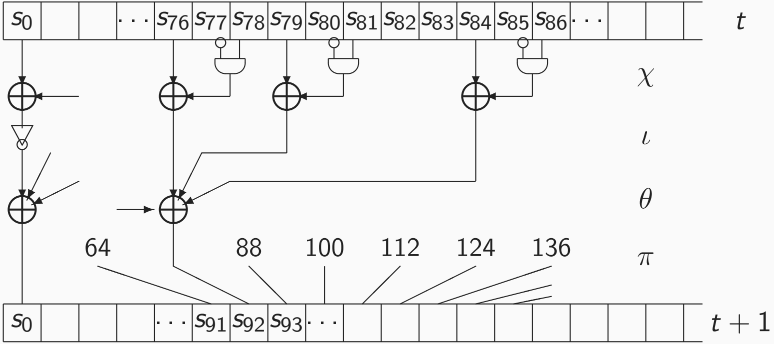
$$\chi: \quad s_i \leftarrow \quad s_i + (s_{i+1} + 1)s_{i+2}$$

$$\iota: \quad s_i \leftarrow \quad s_i + \delta_i$$

$$\theta: \quad s_i \leftarrow \quad s_i + s_{i+3} + s_{i+8}$$

$$\pi: \quad s_i \leftarrow \quad s_{12i}$$

Absorb and Squeeze



$$12^4 = 176$$

$$\mathcal{G}_{64} = \{1, 176, 136, \ldots, 92\} \prec \mathbb{Z}/257\mathbb{Z}^*$$

$$z_i = s_{176^i} + s_{176^{-i}}$$

$$s_{176^i} = s_{176^i} + p_i$$

The choice of $\mathcal{G}_{64}$:

- non-consecutive bits (State-Recovery attacks on Ketje Jr [Fuhr, Naya-Plasencia, Rotella, ToSC 2018])
- consistent with π dispersion

Design Rationale in a nutshell

The choice of $\mathcal{G}_{64}$:

- non-consecutive bits (State-Recovery attacks on Ketje Jr [Fuhr, Naya-Plasencia, Rotella, ToSC 2018])
- consistent with π dispersion

The number of rounds:

- Separator: 8 blank rounds
- Unkeyed mode: 2 rounds ($8 + 1$ bits absorbed)
- Keyed mode: 1 round ($32 + 1$ bits absorbed)

Third Party Cryptanalysis

Fukang Liu, Takanori Isobe and Willi Meier, Cube-Based Cryptanalysis of Subterranean-SAE, ToSC 2020

- key recovery from Subterranean-SAE in nonce-misuse scenario
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More work is welcome

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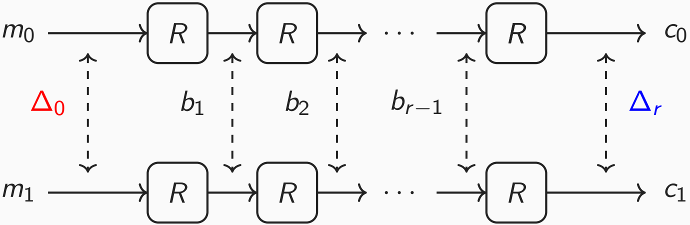
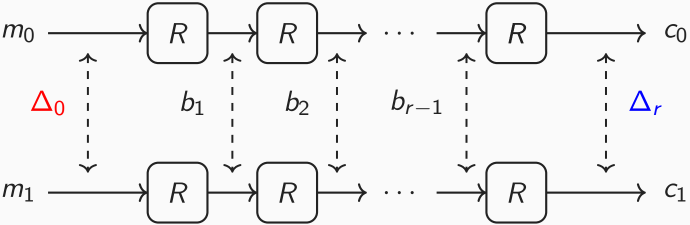


- Security: $\max \mathrm{DP}(\Delta_0 \to \Delta_r)$
  It is hard to determine
- $\max \mathrm{DP}(\Delta_0 \to \Delta_r) \approx \max_{Q_r} \mathrm{DP}(Q_r)$
  - Q_r is a differential trail
  - $\Delta_0 \to b_1 \to b_2 \to \cdots \to b_{r-1} \to \Delta_r$

Difference propagation



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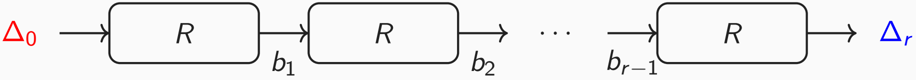
  - $\Delta_0 \to b_1 \to b_2 \to \cdots \to b_{r-1} \to \Delta_r$
- Trail weight: $w(Q) = -\log_2(\mathrm{DP})$

Differential trail core



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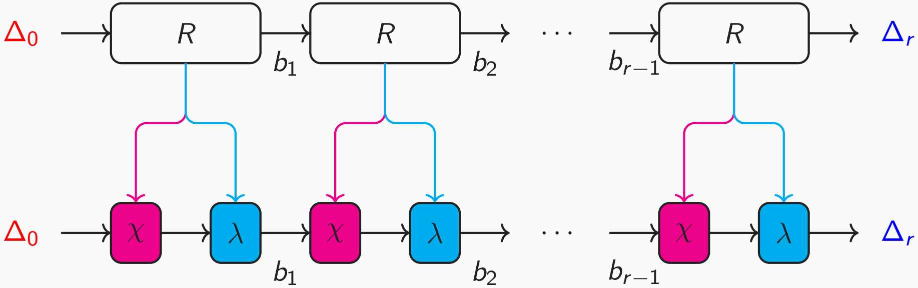

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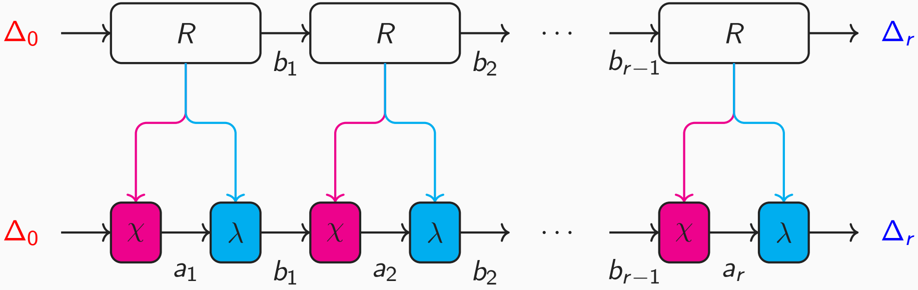

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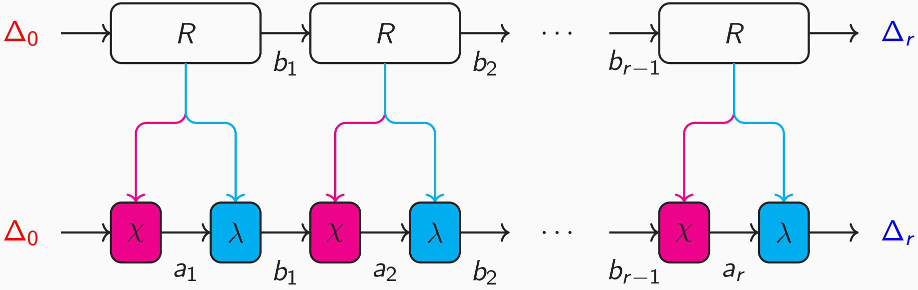

$$w(Q_r) = w(\Delta_0 \to a_1) + \sum_{i=1}^{r-1} w(b_i \to a_{i+1})$$

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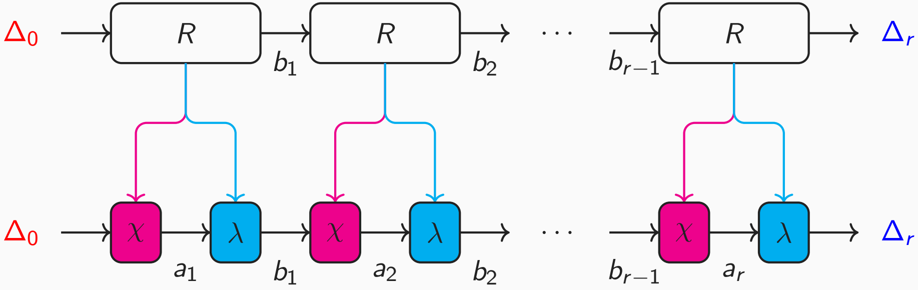

$$w(Q_r) = w(\Delta_0 \to a_1) + \sum_{i=1}^{r-1} w(b_i \to a_{i+1}) = \min w^{-1}(a_1) + \sum_{i=1}^{r-1} w(b_i)$$

Lower bound on the weight of differential trail cores

# rounds:	1	2	3	4	5	6	7	8
lower bound:	?	?	?	?	?	?	?	?

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- We generated all 3-round trails cores up to weight 39
  The same method as introduced in [Mella, Daemen, Van Assche, ToSC 2016]

Lower bound on the weight of differential trail cores

# rounds:	1	2	3	4	5	6	7	8
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  The same method as introduced in [Mella, Daemen, Van Assche, ToSC 2016]

weight	25	28	29	30	32	33	34	35	36	37	38	39
# trail cores (mod *rotation*)	1	1	2	3	2	1	5	6	4	9	12	17

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# trail cores (mod *rotation*)	1	1	2	3	2	1	5	6	4	9	12	17

- 3-round trail core with the lowest weight

state	**weight**	**# active bits**	**active bit positions**
a_1	2	1	$\{0\}$
b_1	6	3	$\{0, 64, 85\}$
b_2	17	9	$\{0, 64, 85, 91, 155, 157, 176, 221, 242\}$

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- We searched the space of all 4-round trail cores up to weight 48

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  - so $49 \leq \min w(Q_4) \leq 58$
- The 4-round trail core with weight 58:

state	weight	# active bits	active bit positions
a_1	12	9	$\{0, 5, 8, 10, 12, 15, 16, 18, 21\}$
b_1	7	5	$\{65, 66, 85, 86, 87\}$
b_2	11	6	$\{7, 28, 134, 198, 200, 219\}$
b_3	28	15	$\{16, 18, 22, 39, 54, 86, 88, 107, 118, 139, 152, 173, 188, 211, 252\}$

Lower bounds on differential trails

# rounds:	1	2	3	4	5	6	7	8
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- If $w(Q_8) \leq (2 \times 48) + 1 = 97$ then $w(Q_4) \leq 48$ or $w(Q'_4) \leq 48$

Lower bounds on differential trails

# rounds:	1	2	3	4	5	6	7	8
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Lower bounds on differential trails

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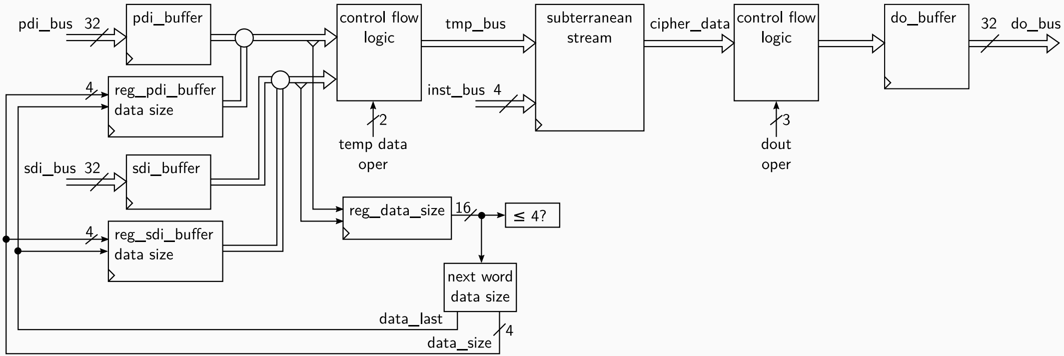
- If $w(Q_8) \leq (2 \times 48) + 1 = 97$ then $w(Q_4) \leq 48$ or $w(Q'_4) \leq 48$
- Different methods to find the lower bound on the weight of other trails

Hardware LWC architecture



- Streaming based architecture - high throughput
- Separate buffers for public and secret data in (PDI/SDI)
- Flow controlled by main state machine

FPGA Results

Mohajerani et al. "FPGA Benchmarking of Round 2 Candidates in the NIST Lightweight Cryptography Standardization Process: Methodology, Metrics, Tools, and Results". https://eprint.iacr.org/2020/1207

- 1st AEAD throughput for messages of 64 bytes or more in Artix 7
- 6th Hash throughput for long messages in Artix 7

AEAD	Throughput	LUT
Subterranean 2.0	6 Gbps	915
Xoodyak	3 Gbps	2040

Hash	Throughput	LUT
Gimli	1.9 Gbps	1900
Xoodyak	1.8 Gbps	2040
Saturnin	1.6 Gbps	2414
DryGascon	1.5 Gbps	2074
Ascon	987 Mbps	1723
Subterranean 2.0	744 Mbps	915

ASIC Results

Khairallah et al. "Preliminary Hardware Benchmarking of a Group of Round 2 NIST Lightweight AEAD Candidates".
`https://github.com/mustafam001/lwc-aead-rtl`

- AEAD for ASIC cells TSMC TSBN 65nm 9-track
- 1st in Throughput and Energy
- Results for 64 bytes messages:

AEAD	Throughput	Area (GE)	Energy (pJ)	Clock period (ns)
Subterranean 2.0	17 Gbps	7050	16	0.47
Romulus	8 Gbps	14218	44	0.88
Xoodyak	12 Gbps	17898	51	0.50

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  - especially non-linear operations → suitable for masking

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  - especially non-linear operations $\rightarrow$ suitable for masking
  - confirmed by benchmarks

Conclusion

SUBTERRANEAN 2.0 in a nutshell:

- Target security strength
  - 128 bits for keyed modes: Deck and SAE
  - 112 bits for unkeyed mode: XOF
- Safety margin is comfortable, per our analysis and two 3rd-party papers
  - more 3rd party cryptanalysis is welcome!
- Lightweight
  - total storage in SAE and XOF: 257-bit state and some 32-bit I/O buffers
  - # operations per absorbed/squeezed bit very low
  - especially non-linear operations → suitable for masking
  - confirmed by benchmarks

Thanks for your attention!