Algebraic Fault Analysis of Subterranean 2.0

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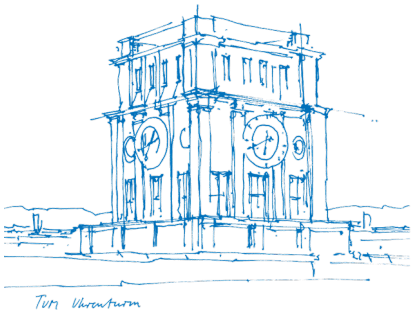


Overview

Motivation

- Demand for lightweight ciphers, e.g. for IoT
  - → Low algebraic degree
  - → Susceptible to Algebraic Fault Analysis

- Algebraic Fault Analysis (AFA)
  - → Analytical/Differential type of Fault Analysis
  - → Model a fault attack as an equation system
  - → Automated solving

→ This work: Breaking Subteranean 2.0 with AFA

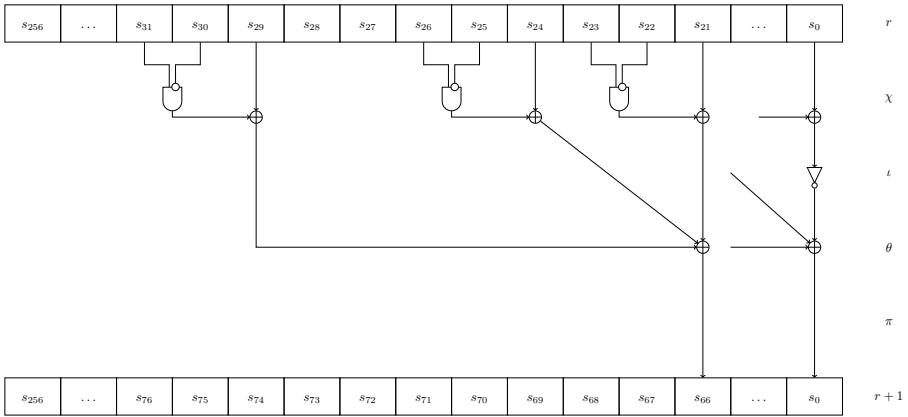
Overview

Subterranean 2.0

- Permutation reused from J. Daemens PhD thesis [3]
- Optimized for hardware implementations
- 2nd round NIST LWC candidate [4]
- Unfortunately not a finalist
- Stream cipher
  - → Low degree ($GF(2)$)
  - → 257-bit state
  - → 128-bit key
  - → non-linear feedback (round function)
- Sponge-like duplex:
  - → Absorb: 33-bit input rate σ
  - → Squeeze: 32-bit output rate (keystream)

$$R = \pi \circ \theta \circ \iota \circ \chi \tag{1}$$

Round Function



Authenticated Encryption Scheme

Algorithm Subterranean SAE

function SUBTERRANEAN-SAE(K, N, AD, PT)

$s \leftarrow 0^{257}$ ▷ Initialization
s.absorb(K)
s.absorb(N)
s.blank(8)

s.absorb(AD) ▷ Processing
$CT \leftarrow$ s.absorb(PT)

s.blank(8) ▷ Finalization
$T \leftarrow$ s.squeeze_tag()

return (CT, T)
end function

Overview

1. Collecting Faulty Outputs

Fault model:

- Fault position/clock cycle p
- Fault location/state index l
- Fault width w
- Bitflip / random bitflip

$\rightarrow$ Adding a w-bit mask to state index l at end of cycle p

$\rightarrow$ Extended Python reference implementation

2. Generate Cipher Equations

Initialization:

$$s_i = 0$$

Data Absorption:

$$s_i^{t_0} = s_i^p + s_{i+1}^p s_{i+2}^p + s_{i+2}^p + \delta_i$$
$$s_i^{t_1} = s_{12i}^{t_0} + s_{12i+3}^{t_0} + s_{12i+8}^{t_0}$$

$$s_i^{p+1} = \begin{cases} s_i^{t_1} + \sigma_j & \text{, if } i \text{ input position} \\ s_i^{t_1} & \text{, otherwise} \end{cases}$$

Encryption of 32-bit word of PT:

$$ct_i = pt_i + s_{12^4 i} + s_{-12^4 i}$$

Squeezing 32-bit word of Tag:

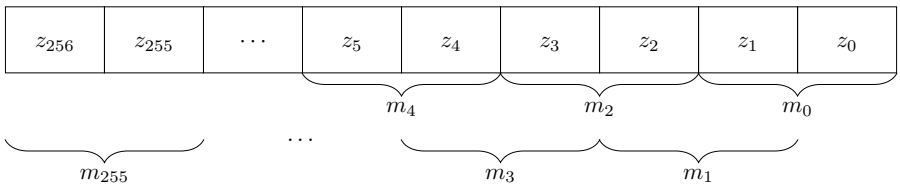
$$t_i = s_{12^4 i} + s_{-12^4 i}$$

3. Generate Fault Equations

- Zhang et al.: Generalized framework [7]
  - → Intermediate state difference
  - → Information on fault model
  - → Equations from fault injection to end of computation

- State difference: $z = s + s^*$

- Split up z into blocks of width w



4. Solve the Equation System

- BOSPHORUS [2] for preprocessing
  - → ANF-CNF conversion
  - → iterative simplification

- CryptoMiniSat5 [6] for solving
  - → conflict driven SAT solver
  - → native XOR support

Overview

Results

1. **Fault Model Evaluation**:
   - Choosing fault location l
   - Optimal fault position p
   - Influence of fault width w

2. **Equation System Optimization**

3. **Measurement Assumptions**

   - Empty message considered
   - 20 instances per measurement, 12 hours
   - Results consider average over all instances

4. **Comparison with Trivium**

Results

Tool	Parameter	CNF	
		non-optimized	optimized
BOSPHORUS	Variables	$70,942$	$71,849$
	Clauses	$440,229$	$178,000$
	Time	2.10 s	$\approx$ 4.5 h
CryptoMiniSat [6]	Time	$>$ 48 h	3.83 s
	Total Time	$>$ 48 h	$\approx$ 4.5 h

Table: Comparison of CNFs with 20 fault injections

$\rightarrow$ Significant benefit when optimizing during preprocessing

Comparison with Trivium

- Trivium [1]: lightweight, hardware-centric stream cipher
- Mohamed et al. [5]
- Careful comparison due to different structure/toolchain/CPU

	Trivium [5]	**Subterranean 2.0**
State size [bit]	288	257
Key size [bit]	80	128
	AFA Results	
No. Faults	2	5
No. Key bits	$420 - 800$	128
Solving time [s]	$0.127 - 138.653$	3.45

Table: Comparison of Trivium and Subterranean 2.0

Thank you for your attention!

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References

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[4] J. Daemen, P. M. C. Massolino, and Y. Rotella. *The Subterranean 2.0 cipher suite*. https://csrc.nist.gov/Projects/lightweight-cryptography/round-2-candidates. 2019.

[5] M. S. E. Mohamed, S. Bulygin, and J. Buchmann. “Using SAT Solving to Improve Differential Fault Analysis of Trivium”. In: *Communications in Computer and Information Science*. Springer Berlin Heidelberg, 2011, pp. 62–71.

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[7] F. Zhang et al. “A Framework for the Analysis and Evaluation of Algebraic Fault Attacks on Lightweight Block Ciphers”. In: *IEEE Transactions on Information Forensics and Security* 11.5 (2016), pp. 1039–1054.