sLiSCP: Simeck-based Permutations for Lightweight Sponge Cryptographic Primitives

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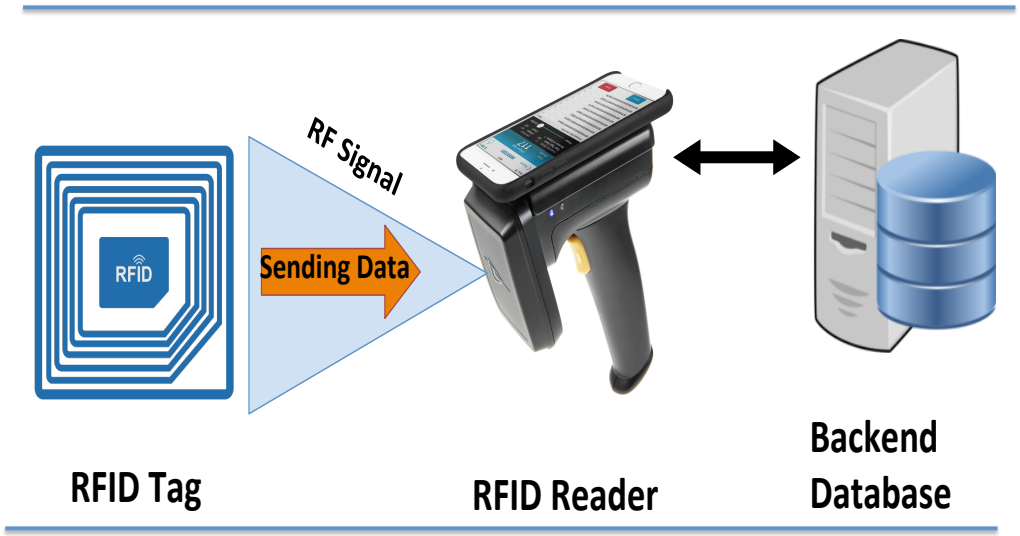
Outline

Motivation

- Lightweight applications such as RFID and sensor networks are resource-constrained in computational and storage aspects.



- Threats to the RFID systems
  - Leaking info about product details
  - Tracking buyers
  - Identifying information of tags

Motivation (2)

- Multiple security services are needed for securing such applications.
  - Privacy
  - Device authentication
  - Privacy-preserving authentication protocol
- For a passive RFID tag (est. 1k - 10k GE), a maximum of 20% of its area (2k GE) can be used for all security functionalities.

Motivation (3)

- Over the last few years, numerous lightweight symmetric-key primitives such as block ciphers, stream ciphers and hash functions have been proposed.
  - Block ciphers:
    - PRESENT
    - PRINCE
    - SIMON and SPECK
    - SIMECK
    - PRIDE
    - SKINNY
  - Stream ciphers: Grain-80/128, Trivium and WG (WG-5,7,8)
  - Hash functions:
    - PHOTON
    - QUARK
    - SPONGENT
    - LHash
- Various authenticated encryption (AE) schemes have been developed.
  - NORX-16 and Ketje-JR; Grain-128a

Need for a design with multiple crypto-functionalities!

Objectives

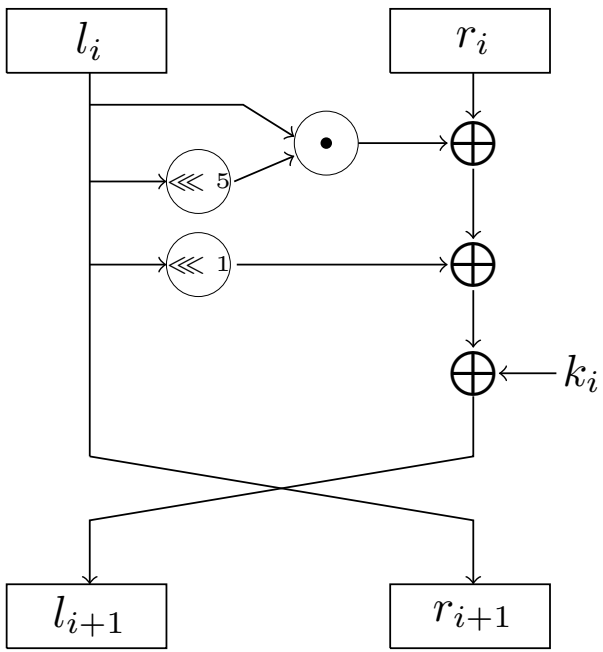
- Providing multiple cryptographic functions with low overhead for lightweight applications
  - Encryption
  - Authentication
  - Hash computation
  - Pseudorandom bit generation
- Efficient hardware implementations
- Providing security guarantees

Contributions

- We design the sLiSCP family of lightweight cryptographic permutations to be used in a unified sponge duplex construction in order to provide (authenticated) encryption and hashing functionalities.
- We implement sLiSCP in CMOS 65 nm ASIC and the area of the parallel architecture is competitive with existing primitives.

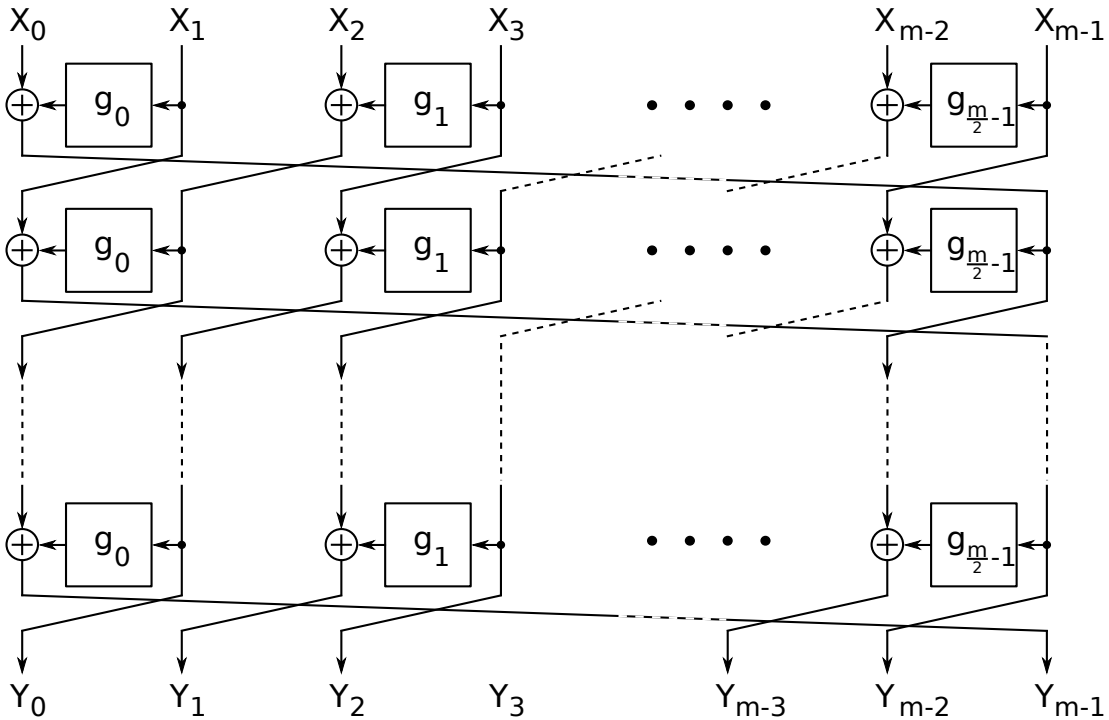
Background: Simeck

- Simeck is a family of block ciphers designed in ComSec lab [Yang et al., CHES 2015]. Its design is based on Simon [Beaulieu et al., eprint 2013/404].
  - Three lightweight instances: Simeck32/64, 48/96, 64/128
  - The Simeck block cipher family is more hardware efficient than the Simon family.

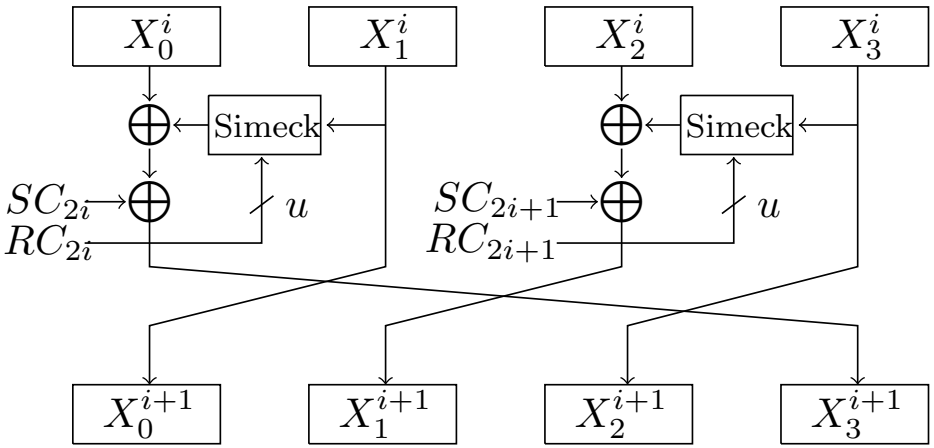


Background: Type 2 GFS

- A Type 2 Generalized Feistel Structure (GFS) [Nyberg, ASIACRYPT'96] is a Feistel network consists of
  - m (even) branches and $\frac{m}{2}$ functions $g_0, g_1, \cdots, g_{\frac{m}{2}-1}$
  - the functions $g_i : \{0,1\}^n \to \{0,1\}^n$



The sLiSCP Family of Permutations



- The sLiSCP is an iterative permutation constructed by combining the Type 2 GFS and round-reduced Simeck cipher.
- Round-reduced Simeck, with no key schedule but round constants added, is used to construct the round function of the GFS.
- Same LFSR is used to generate Simeck^u-m and Feistel round constants.

The sLiSCP Family of Permutations (2)

- Let $h_t^u(\cdot)$ denote the u-round Simeck^u-m box.
- The round function $f : \mathbb{F}_2^{4m} \to \mathbb{F}_2^{4m}$ of sLiSCP is given by

$$
\begin{aligned}
&(X_0^{i+1}, X_1^{i+1}, X_2^{i+1}, X_3^{i+1}) = f(X_0^i, X_1^i, X_2^i, X_3^i) \text{ where} \\
&X_0^{i+1} = X_1^i \\
&X_1^{i+1} = h_t^u(X_3^i) + X_2^i + SC_{2i}, t = RC_{2i} \\
&X_2^{i+1} = X_3^i \\
&X_3^{i+1} = h_t^u(X_1^i) + X_0^i + SC_{2i+1}, t = RC_{2i+1}
\end{aligned}
$$

- On input $(X_0^0, X_1^0, X_2^0, X_3^0)$, the output of an s-step sLiSCP permutation F is given by

$$(X_0^s, X_1^s, X_2^s, X_3^s) = F(X_0^0, X_1^0, X_2^0, X_3^0) = f^s(X_0^0, X_1^0, X_2^0, X_3^0).$$

- An LFSR is employed to generate step constants and round constants.
  - Simeck constants are called *round* constants RC_j
  - Feistel structure constants are called *step* constants SC_j

Two sLiSCP Instances

- There are two lightweight instances of sLiSCP.
- sLiSCP-192: $(\mathbb{F}_2^{48})^4 \rightarrow (\mathbb{F}_2^{48})^4$
  - Internal state size $= 192$
  - Simeck-48 is employed (i.e., $m = 48$)
  - # of Simeck rounds $= 6$
  - # of Feistel steps $= 18$
  - An LFSR of degree 6 is used: $x^6 + x + 1$.
- sLiSCP-256: $(\mathbb{F}_2^{64})^4 \rightarrow (\mathbb{F}_2^{64})^4$
  - Internal state size $= 256$
  - Simeck-64 is employed (i.e., $m = 64$)
  - # of Simeck rounds $= 8$
  - # of Feistel steps $= 18$
  - An LFSR of degree 7 is used: $x^7 + x + 1$.

Permutation (b-bit)	Subblock width m	Rounds u	Steps s	Total # rounds ($u \cdot s$)
sLiSCP-192	48	6	18	108
sLiSCP-256	64	8	18	144

Security Analysis: sLiSCP Design Security Goals

- Bounds against differential and linear cryptanalysis
  - Consider the u-round Simeck round function as an Sbox and use SAT/SMT and MILP tools to provide bounds based on the minimum number of active Sboxes.
- Resistance against diffusion-based attacks
  - Choosing the number of steps equals three times the number of rounds required for the full bit diffusion.
- Resistance against algebraic attacks
  - Choosing the number of rounds that provides an adequate growth of algebraic degree.

Security Analysis: Differential and Linear Cryptanalysis

- Employing an SAT/SMT tool, tightly bound the estimated maximum differential probability (MEDP) of the Simeck boxes

Rounds (u)	1	2	3	4	5	6	7	8	9
MEDP (Simeck^u-48)	0	-2	-4	-6	-8	-11.299	-13.298	-16.597	-18.595

- Develop a MILP model to bound the minimum number of active Simeck boxes h_t^u.

Step	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Min. # of active h_t^u	0	1	2	3	4	6	6	7	8	9	10	12	12	13	14	15	16	18

- Then the MEDCP of sLiSCP-192, and sLiSCP-256 are:

$$\text{MEDCP} = \text{MEDP}(\text{Simeck}^6\text{-}48)^{18} = (2^{-11.299})^{18} = 2^{-203.382}$$
$$\text{MEDCP} = \text{MEDP}(\text{Simeck}^8\text{-}64)^{18} = (2^{-16.597})^{18} = 2^{-298.746}$$

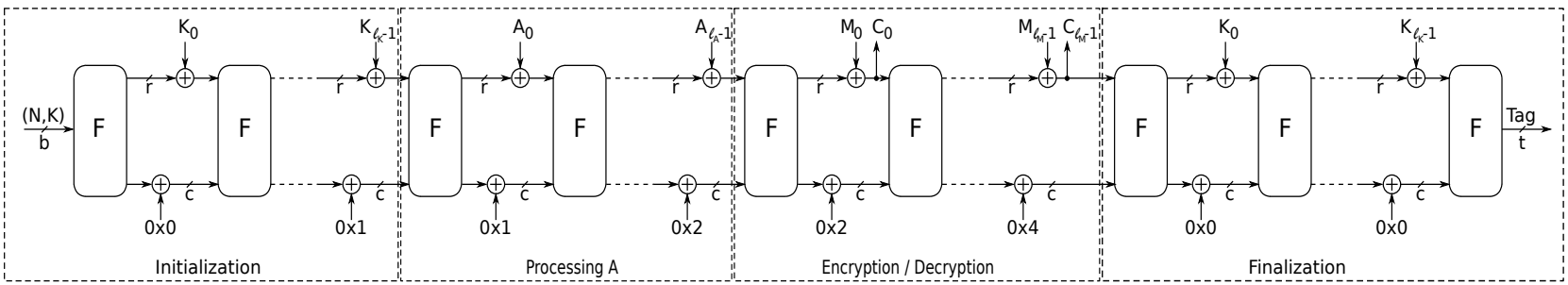
- The maximum expected linear characteristic correlation (MELCC) can be computed analogously.

A Summary of the Distinguishing Complexities

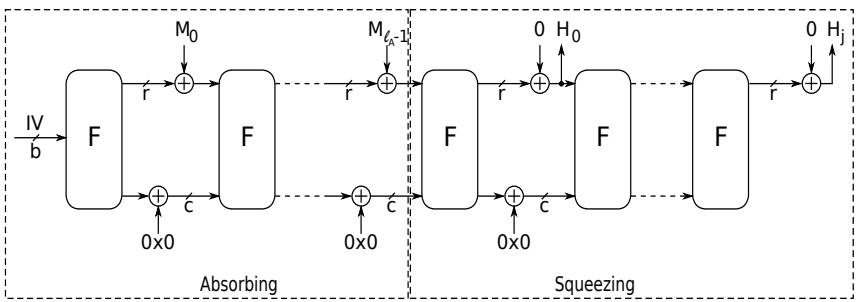
Attacks	Complexity	# steps	Remark
	sLiSCP-**192**		
Differential cryptanalysis	$2^{203.382}$	18	
Linear cryptanalysis	$2^{203.382}$	18	
Integral Distinguishers	2^{188}	9	Division property
Zero-sum Distinguishers	2^{111}	6 (7)	Basic zero-sum (1 extra step)
	2^{158}	8 (9)	Basic zero-sum (1 extra step)
	2^{190}	17	Partial zero-sum (Div. prop.)
	sLiSCP-**256**		
Differential cryptanalysis	$2^{298.746}$	18	
Linear cryptanalysis	$2^{295.2}$	18	
Integral Distinguishers	2^{255}	9	Division property
Zero-sum Distinguishers	2^{178}	6	Basic zero-sum (1 extra step)
	2^{241}	8	Basic zero-sum (1 extra step)
	2^{255}	17	Partial zero-sum (Div. prop.)

Constructing AE and Hash from sLiSCP

- Our goal is to provide as many cryptographic functionalities as possible such as authenticated encryption, stream cipher, MAC and hash function.
- We use the sLiSCP permutation as a unified round function in the sponge construction to design multiple crypto-functionalities.



(a) Authenticated Encryption Mode



(b) Hash Mode

AE and Hash Instances

- There are three instances of authenticated encryption schemes of sLiSCP, denoted by sLiSCP-b/k, with different key and tag sizes.

Algorithm	Key	Nonce	Tag	Block size r	Capacity c	Usage exponent a	Security claim
sLiSCP-192/80	80	80	80	32	160	72	80
sLiSCP-192/112	112	80	112	32	160	40	112
sLiSCP-256/128	128	128	128	64	192	56	128

- There are three instances of hash functions, constructed from sLiSCP, with different hash sizes.

Algorithm	IV	h	r	r'	c	collision	Sec. preimage	Primage
sLiSCP-192	$0x502020$	160	32	32	160	80	80	128
sLiSCP-256	$0x604040$	192	64	64	192	96	96	128
sLiSCP-256	$0x604020$	192	64	32	192	96	96	160

Hardware Implementation Results

- We implemented the sLiSCP instances in the CMOS 65 nm technology.
- The areas for sLiSCP-192 and sLiSCP-256 are given below.

Permutation F	**Process** (nm)	**Area** (GEs)
sLiSCP-192	65	2153
sLiSCP-256	65	2833

- The AE and hash modes consume more XOR gates. The areas for sLiSCP-192 and sLiSCP-256 modes are given below.

Hash	**Process** (nm)	**Area** (GEs)	**AE**	**Process** (nm)	**Area** (GEs)
sLiSCP-192 ($r' = 32$)	65	2271	sLiSCP-192/80	65	2289
sLiSCP-256 ($r' = 64$)	65	3019	sLiSCP-192/112	65	2289
sLiSCP-256 ($r' = 32$)	65	3019	sLiSCP-256/128	65	3039

Hardware implementation results on 130 nm tech. are available in the full paper.

Comparisons with Other Primitives

Hash function	**Parameters**				**Security (bits)**			**Process**	**Latency**	**Area**	**Throughput**
	r	c	r'	h	Pre	2nd Pre.	Coll.	(nm)	(Cycles)	(GEs)	(kbps)
sLiSCP-**192**	32	160	32	160	128	80	80	65	108	**2271**	29.62
Photon-160/36/36	36	160	36	160	124	80	80	180	180	2117	20.00
D-Quark	16	160	16	176	160	80	80	180	88	2819	18.18
Spongent-160/160/16	16	160	16	160	144	80	80	130	90	2190	17.78
Keccak-f[40,160]	40	160	40	200	160	160	80	130	18	4900	222.22
Keccak-f[72,128]	72	128	72	200	128	128	64	130	18	4900	400.00
sLiSCP-**256**	64	192	64	192	128	96	96	65	144	**3019**	44.44
sLiSCP-**256**	64	192	32	192	160	96	96	65	144	**3019**	22.22
Photon-224/32/32	32	224	32	224	192	112	112	180	204	2786	15.69
Spongent-160/160/80	80	160	80	160	80	80	80	130	120	3139	66.67
Spongent-224/224/16	16	224	16	224	208	112	112	130	120	2903	13.33
Spongent-256/256/16	16	256	16	256	240	128	128	130	140	3281	11.43
S-Quark	32	224	32	256	224	112	112	180	64	4640	50
AE algorithm				t	Con.	Int.					
sLiSCP-**192/80**	32	160	32	80	80	80	-	65	108	**2289**	29.62
sLiSCP-**192/112**	32	160	32	112	112	112	-	65	108	**2289**	29.62
sLiSCP-**256/128**	64	192	64	128	128	128	-	65	144	**3039**	44.44
Ketje-Jr	16	184	16	96	96	96	-	-	-	4900	-
NORX-16	128	128	128	96	96	96	-	-	-	2880	-

Conclusions

In this paper:

- we proposed a family of lightweight permutations based on Simeck and Type 2 GFS structure.
- two instances of the permutation are presented and their security has been analyzed against known distinguishing attacks.
- we proposed total six instances of authenticated encryption and hash modes of sLiSCP using the sponge function.
- we implemented all the instances in ASICs with 65 nm technology.

  - sLiSCP-192: 2271 (rate 32)
  - sLiSCP-256: 3019 (rate 64)
  - sLiSCP-256: 3019 (rate 32)
  - sLiSCP-192/80: 2289
  - sLiSCP-192/112: 2289
  - sLiSCP-256/128: 3039

- Full paper can be found at:
  https://eprint.iacr.org/2017/747.pdf
  http://cacr.uwaterloo.ca/techreports/2017/cacr2017-04.pdf

Thank you for your attention!

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