SpoC: An Authenticated Cipher
Submission to the NIST LWC Competition

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Chapter 1

Introduction

In a nutshell, Sponge with masked Capacity, or SpoC (pronounced as Spock), is a permutation based mode of operation for authenticated encryption with associated data (henceforth “AEAD”) functionality. The high level design is inspired by the Beetle [9, 10] mode of operation. It offers higher security guarantee with smaller states as compared to some of the previous AEAD designs based on the Sponge paradigm [7, 8, 11, 12]. In what follows, we briefly highlight the features of SpoC and then introduce the notations used throughout the document.

- **Novelty.** Capacity is masked with data blocks instead of rate which improves the security and allows larger rate value per permutation call.

- **Control bits.** A 4-bit control signal which distinguishes different phases and does not require an extra call of permutation in the case of empty and partial data blocks.

- **Underlying permutation.** Adopts a lightweight permutation sLiSCP-light [4] which is efficient in both hardware and software because of bitwise and cyclic shift operations.

- **Security.** 128-bit security with state sizes 192 and 256, and corresponding rate values 64 and 128 bits, respectively.

- **Hardware footprint.** Smaller instance has an area of 2329 GE in ASIC CMOS 65nm and achieves a throughput of 58.3 kbps for 1KB message, which fits the requirements of constrained devices.
1.1 Notations

In the following, \( n \) denotes a non-negative integer. We use \( \{0,1\}^+ \) and \( \{0,1\}^n \) to denote the set of all non-empty (binary) strings, and \( n \)-bit strings, respectively. \( \bot \) denotes the empty string and \( \{0,1\}^* = \{0,1\}^+ \cup \{\bot\} \). For any string \( B \in \{0,1\}^+ \), \( |B| \) denotes the number of bits in \( B \) and by \( (B_0, \ldots, B_{\ell-1}) \leftarrow^n B \), we refer to the \( n \)-bit block parsing of \( B \) into \( (B_0, \ldots, B_{\ell-1}) \), where \( |B_i| = n \) for \( 0 \leq i \leq \ell - 2 \), and \( 1 \leq |B_{\ell-1}| \leq n \). Moreover, \( B_i[j] \) denotes the \( j \)-th byte of \( B_i \) (starting from left). For \( A, B \in \{0,1\}^+ \), and \( |A| = |B| \), \( A \oplus B \) (resp. \( A \odot B \)) denotes the “bitwise XOR” (resp. “bitwise AND”) operation on \( A \) and \( B \), and \( A \parallel B \) denotes the “string concatenation” operation. For \( x \in \{0,1\}^n \), \( L^i(x) \) denotes the left cyclic shift operator, i.e., \( L^i(x) = (x_i, x_{i+1}, \ldots, x_{n-1}, x_0, x_1, \ldots, x_{i-1}) \).

We fix positive even integers \( b, t \) and \( n \) to denote the state size, tag size and nonce size, respectively in bits. \( \Pi \) denotes a permutation over \( \{0,1\}^b \). We fix integers \( r \) and \( c := b - r \) as the rate and capacity of the permutation \( \Pi \). With regard to rate and capacity, we use the following conventions:

- **Rate denotes the size of the amount of key stream bits (also called rate bits) generated per call of \( \Pi \).** By definition, capacity denotes the difference between block size and rate.

- **For simplicity, we fix the \( r \) least significant bits as the rate bits and the remaining \( c = b - r \) most significant bits as the capacity bits.**

1.2 Outline

The rest of the document is organized as follows. In Chapter 2, we present the complete specification of \( \text{SpoC} \) along with its underlying permutation and recommended instances. We summarize the security claims of \( \text{SpoC} \) in Chapter 3 and provide the detailed security analysis in Chapter 4. In Chapter 5, we present the rationale of our design choices. Finally, we conclude by providing the details of hardware implementation in ASIC CMOS and performance results in Chapter 6.
Chapter 2
Specification

In this chapter, we present the specifications of SpoC along with its underlying permutation. We also give a detailed overall algorithmic description of the whole cipher and then list the recommended instances of SpoC.

2.1 SpoC Parameters

SpoC is primarily parameterized by the rate $r$ of the underlying permutation, where $r \in \{64, 128\}$. We simply write SpoC-$r$ to denote SpoC with the particular choice of $r$. The secondary parameters are set as follows.

- **SpoC-64**: In this version, $c = 128$, i.e., $b = 192$; $n = 128$; and $t = 64$.
- **SpoC-128**: In this version, $c = 128$, i.e., $b = 256$; $n = 128$; and $t = 128$.

In both versions, we set the key size $\kappa$ same as the capacity, i.e., $\kappa = c$.

2.2 Description of SpoC

The SpoC’s state can be viewed as an $(c,r)$-bit concatenated string $Y||Z$ (sometimes, also viewed as $(Y,Z)$) made up of $c$-bit string $Y$ (also called the $Y$-state) and $r$-bit string $Z$ (also called the $Z$-state). In Algorithms 1 and 2, we present the complete algorithmic description of the mode, and Figure 2.1 illustrates the major components of the encryption/decryption process. We now give a high level description of the main modules (given in Algorithm 2) used in the encryption/decryption (described in Algorithm 1) process.

- **init**: The major task of this module is to create the initial state using the public nonce $N = N_0||N_1$ and the secret key $K = K_0||K_1$. We denote this state by $Y_0||Z_0$ and is formally given as follows.

\[
Y_0||Z_0 = \begin{cases} 
\Pi(\text{load-SpoC-64}(N_0, K)) \oplus (N_1||0^{b-r}) & \text{for SpoC-64,} \\
\text{load-SpoC-128}(N, K) & \text{for SpoC-128.}
\end{cases}
\]

The function load-SpoC-$r$(·) depends on the choice of $\Pi$ and assigns the nonce and key bytes to the particular byte positions of the state. We explicitly define this function in Section 2.6.
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- **proc_ad**: This module is responsible for the associated data (AD) processing. During this phase, the control signal is set to 0010 to indicate a non-empty AD block. In case of partial block\(^1\), the control signal changes to 0011. The entire AD processing step is given in “function proc_ad” of Algorithm 2.

- **proc_pt**: This module is responsible for the processing of plaintext (PT). During this phase, the control signal is set to 0100 to indicate a non-empty PT block. In case of partial block, the control signal changes to 0101. PT processing is similar to AD processing except for the fact that we squeeze out \( r \)-bit ciphertext and XOR the control signal (after extracting \( r \)-bit keystream). The entire PT processing step is given in “function proc_pt” of Algorithm 2.

- **proc_ct**: This module is responsible for ciphertext (CT) processing. It is symmetrical to proc_pt, and given in “function proc_ct” of Algorithm 2.

- **proc_tg**: This module is responsible for tag generation. At the tag generation call, the control signal is of the form 1xyz, where the 3 least significant bits xyz depend on the previous modules. More details on the control signals is given below. We denote the process of extracting tag from state by \( \text{tagextract-SpoC-r} \). More details are given in “function proc_tg” of Algorithm 2 and Section 2.7.

**Algorithm 1** Encryption/Decryption algorithm in SpoC.

```plaintext
1: function SpoC\_r\_\Pi.enc(K, N, A, M) 1: function SpoC\_r\_\Pi.dec(K, N, A, C, T)
2: C \leftarrow \perp 2: M \leftarrow \perp
3: (Y_0, Z_0, a, m, ℓ) \leftarrow \text{init}(K, N, A, M) 3: \text{is\_auth} \leftarrow 0
4: if \ a \neq 0 \ then 4: (Y_0, Z_0, a, m, ℓ) \leftarrow \text{init}(K, N, A, C)
5: (X_a, Z_a) \leftarrow \text{proc\_ad}(Y_0, Z_0, A) 5: if \ a \neq 0 \ then
6: if \ m \neq 0 \ then 6: (X_a, Z_a) \leftarrow \text{proc\_ad}(Y_0, Z_0, A)
7: (X_ℓ, Z_ℓ, C) \leftarrow \text{proc\_pt}(X_a, Z_a, M) 7: if \ m \neq 0 \ then
8: \ T \leftarrow \text{proc\_tg}(X_ℓ, Z_ℓ) 8: (X_ℓ, Z_ℓ, M) \leftarrow \text{proc\_ct}(X_a, Z_a, C)
9: \text{return} (C, T) 9: \ T' \leftarrow \text{proc\_tg}(X_ℓ, Z_ℓ)
10: \text{if} \ T' = T \text{ then} 10: \text{if} \ T' = T \text{ then}
11: \ \text{is\_auth} \leftarrow 1 11: \ \text{is\_auth} \leftarrow 1
12: \text{else} 12: \text{else}
13: \ M \leftarrow \perp 13: \ M \leftarrow \perp
14: \text{return} (\text{is\_auth}, M) 14: \text{return} (\text{is\_auth}, M)
```

**The Control Signal.** Here we explain the 4-bit control signal that we use to separate the processing of various critical blocks. The control signal, denoted ctrl, can be viewed as a 4-bit string described below

\[
\text{ctrl} := \text{ctrl}_\text{tag} \text{ctrl}_\text{pt} \text{ctrl}_\text{ad} \text{ctrl}_\text{par}
\]

Initially, all control bits are set to 0. The bits are set to 1 in the following manner:

1. **ctrl_ad**: The bit sets to 1 during the processing of associated data blocks. For empty AD it remains set to 0.
2. **ctrl_pt**: The bit sets to 1 during the processing of plaintext blocks. For empty messages it remains set to 0.
3. **ctrl_par**: The bit sets to 1 at the last AD (PT) block processing call if the last block is partial. For full last block it remains set to 0.

\(^1\text{This is only possible if the current block is the last block.}\)
Algorithm 2: Main modules of SpoC.

1: function init(K, N, A, M)
2: if r = c then
3: Y₀||Z₀ ← load-SpoC-128(N, K)
4: else
5: Y₀||Z₀ ← Π(load-SpoC-64(N₀, K)) ⊕ (N₁||0^b−r)
6: a ← ⌊A/r⌋
7: m ← ⌈[M/r]⌉
8: ℓ ← a + m
9: return (Y₀, Z₀, a, m, ℓ)
10: function proc_pt(Yₐ, Zₐ, M)
11: (M₀, ..., Mₘ₋₁) ← parse(M)
12: for j = 0 to m − 2 do
13: k ← a + j
14: Xₖ₊₁∥Zₖ₊₁ ← Π(Yₖ||Zₖ)
15: Cₖ ← Zₖ₊₁ ⊕ Mₖ
16: Yₖ₊₁ ← Xₖ₊₁ ⊕ opt_oz_pad(Mₖ)
17: Zₖ₊₁ ← Zₖ₊₁ ⊕ 0100∥0^r−4
18: Xᵣ∥Zᵣ ← Π(Yᵣ−₁||Zᵣ−₁)
19: Cᵣ−₁ ← chop(Zᵣ, |Mᵣ−₁|) ⊕ Mᵣ−₁
20: C ← (C₀, ..., Cᵣ−₁)
21: Yᵣ ← Xᵣ ⊕ opt_oz_pad(Mᵣ−₁)
22: if r ⊥ Mᵣ−₁ then
23: Zᵣ ← Zᵣ ⊕ 0101∥0^r−4
24: else
25: Zᵣ ← Zᵣ ⊕ 0100∥0^r−4
26: return (Yᵣ, Zᵣ, C)
27: function proc_kg(Yᵣ, Zᵣ)
28: Zᵣ ← Zᵣ ⊕ 1000∥0^r−4
29: if r = c then
30: T ← tagextract-SpoC-128(Π(Yᵣ||Zᵣ), r)
31: else
32: T ← tagextract-SpoC-64(Π(Yᵣ||Zᵣ), r)
33: return T
34: function parse(I)
35: ℓ = ⌈|I|/r⌉
36: if ℓ = 0 then
37: return ⊥
38: else
39: (I₀, ..., I₉−₁) ← I
40: return (I₀, ..., I₉−₁)
41: function proc_ad(Y₀, Z₀, A)
42: (A₀, ..., A₉−₁) ← parse(A)
43: for i = 0 to a − 2 do
44: Xᵢ₊₁∥Zᵢ₊₁ ← Π(Yᵢ∥Zᵢ)
45: Yᵢ₊₁ ← Xᵢ₊₁ ⊕ opt_oz_pad(Aᵢ)
46: Zᵢ₊₁ ← Zᵢ₊₁ ⊕ 0010∥0^r−4
47: Xᵣ∥Zᵣ ← Π(Yᵣ−₁||Zᵣ−₁)
48: Yᵣ ← Xᵣ ⊕ opt_oz_pad(Aᵣ−₁)
49: if r ⊥ Aᵣ−₁ then
50: Zᵣ ← Zᵣ ⊕ 0011∥0^r−4
51: else
52: Zᵣ ← Zᵣ ⊕ 0010∥0^r−4
53: return (Yᵣ, Zᵣ)
54: function chop(I, ℓ)
55: if ℓ > r then
56: return ⊥
57: else
58: (I₀, ..., Iᵣ−₁) ← I
59: return (I₀∥...∥Iᵣ−₁)
60: function opt_oz_pad(I)
61: if r ⊥ |I| then
62: ξ = r − |I| mod r
63: I ← I∥0^(r−1)
64: return |I|/0^r−r

4. ctrl_tag: The bit sets to 1 at tag generation call.

We XOR the ctrl to the four most significant bits of the rate bits (the Z-state). In message processing phase, this is done after the extraction of keystream bits. Table 2.1 enumerates all possible values for the control signal along with their meanings.
Table 2.1: Possible values for the control signal along with their meanings.

<table>
<thead>
<tr>
<th>ctrl</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>Implicitly used in nonce processing.</td>
</tr>
<tr>
<td>0010</td>
<td>Full AD block processing.</td>
</tr>
<tr>
<td>0011</td>
<td>Partial AD block processing.</td>
</tr>
<tr>
<td>0100</td>
<td>Full PT/CT block processing.</td>
</tr>
<tr>
<td>0101</td>
<td>Partial PT/CT block processing.</td>
</tr>
<tr>
<td>1000</td>
<td>Tag generation in empty AD and PT/CT case.</td>
</tr>
<tr>
<td>1010</td>
<td>Tag generation in non-empty AD with full last block and empty PT/CT case.</td>
</tr>
<tr>
<td>1011</td>
<td>Tag generation in non-empty AD with partial last block and empty PT/CT case.</td>
</tr>
<tr>
<td>1100</td>
<td>Tag generation in (non-)empty AD and non-empty PT/CT with full last block case.</td>
</tr>
<tr>
<td>1101</td>
<td>Tag generation in (non-)empty AD and non-empty PT/CT with partial last block case.</td>
</tr>
</tbody>
</table>

2.3 The sLiSCP-light Permutation

sLiSCP-light [4] is a family of iterated permutations based on the partial Substitution Permutation Network (SPN) construction. In this section, we describe the design of the sLiSCP-light family of permutations.

2.3.1 Step function of the permutation

An $s$-step sLiSCP-light permutation takes an input of $b$ bits from $\{0, 1\}^b$ and produces an output of $b$ bits after applying the step function $s$ times sequentially where $b = 8 \times m$ and $m \in \{24, 32\}$. We denote by sLiSCP-light-[$b$] a $b$-bit sLiSCP-light permutation. A high-level overview of the step function of sLiSCP-light is depicted in Figure 2.2.

The state of the permutation is divided into 4 $2m$-bit subblocks $(S_i^0, S_i^1, S_i^2, S_i^3)$, where $i$ denotes the step number and $0 \leq i \leq s - 1$. In each step, the state is updated by a sequence of three transformations: SubstituteSubblocks ($SSb$), AddStepconstants ($ASC$), and MixSubblocks ($MSb$), thus the step function is defined as

$$(S_{i+1}^0, S_{i+1}^1, S_{i+1}^2, S_{i+1}^3) \leftarrow MSb \circ ASC \circ SSb(S_i^0, S_i^1, S_i^2, S_i^3).$$

We now describe each transformation in detail.

**SubstituteSubblocks ($SSb$)**

This is a partial substitution layer of the SPN structure where the nonlinear operation is applied to the half of the state. It applies the $u$-round iterated unkeyed Simeck-2$m$ block cipher [17] (henceforth referred to as Simeck box or $SB_u^{2m}$) to the odd indexed subblocks only. The $SSb$ transformation is defined as

$$SSb(S_i^0, S_i^1, S_i^2, S_i^3) = (S_i^0, SB_u^{2m}(S_i^1), S_i^2, SB_u^{2m}(S_i^3)).$$

Below we provide the details of Simeck box $SB_u^{2m}$. 
Figure 2.1: Schematic diagram of different modules used in the encryption algorithm of SpoC-64 for non-empty AD and PT. From left to right and top to bottom, we have the following modules: init, proc_ad, proc_pt, and proc_tg. SpoC-128 is identical to SpoC-64 except for the init module. In which case we define $Y_0 \parallel Z_0$ as load-SpoC-128($N, K$). Moreover, we apply tagextract-SpoC-128 to generate the tag. See Algorithms 1 and 2 for more details.

Definition 1 (Simeck box $\text{SB}_{2m}^u$ [3]) Let $u > 0$ and $rc = (q_{u-1}, \ldots, q_0)$ where $q_j \in \{0, 1\}$ and $0 \leq j \leq u - 1$. A Simeck box is a permutation of $2m$-bit input constructed by iterating the Simeck-$2m$ block cipher for $u$ rounds with round constant addition $\gamma_j = 1^{m-1} || q_j$ in place of key addition.

An illustrated description of the Simeck box is shown in Figure 2.3 and is given by:

$$(x_{u+1} || x_u) \leftarrow \text{SB}_{2m}^u(x_1 || x_0, rc)$$

where

$$x_j \leftarrow f_{(5,0,1)}(x_{j-1}) \oplus x_{j-2} \oplus \gamma_{j-2}, \ 2 \leq j \leq u + 1 \text{ and}$$

$f_{(5,0,1)} : \{0, 1\}^m \to \{0, 1\}^m$ given by $f_{(5,0,1)}(x) = (L^5(x) \odot x) \oplus L^1(x)$. 

10
AddStepconstants (ASc)

In this layer, the step constants $SC^i_0$ and $SC^i_1$ are XORed with the two even indexed subblocks $S^i_0$ and $S^i_2$, respectively, $i = 0, 1, \ldots, s - 1$. Each $SC^i_j$ is an $2m$-bit constant of the form $1^{2m-\delta}(0||sc^i_j)$ for $(u, m) = (6, 24)$ (resp. $(u, m) = (8, 32)$), where $sc^i_j$ is a 6 (resp. 8)-bit constant generated by an LFSR. The ASc transformation is given by

$$ASc(S^i_0, SB^m_u(S^i_1), S^i_2, SB^m_u(S^i_3)) = (S^i_0 \oplus SC^i_0, SB^m_u(S^i_1), S^i_2 \oplus SC^i_1, SB^m_u(S^i_3)).$$

MixSubblocks (MSb)

This layer applies the linear transformation that is used in the Type-2 GFS [15] to the subblocks of the state. More precisely, each even indexed subblock is replaced by the XOR of its initial value with its neighboring odd indexed subblock. Then a subblock cyclic left shift is applied. The MSb transformation is given by

$$(S^{i+1}_0, S^{i+1}_1, S^{i+1}_2, S^{i+1}_3) \leftarrow MSb(S^i_0 \oplus SC^i_0, SB^m_u(S^i_1), S^i_2 \oplus SC^i_1, SB^m_u(S^i_3)),$$

where

$$S^{i+1}_0 = SB^m_u(S^i_1), \quad S^{i+1}_1 = S^i_2 \oplus SB^m_u(S^i_3) \oplus SC^i_1,$$

$$S^{i+1}_2 = SB^m_u(S^i_3), \quad S^{i+1}_3 = S^i_0 \oplus SB^m_u(X^i_1) \oplus SC^i_0.$$

2.3.2 sLiSCP-light permutation instances

sLiSCP-light offers two lightweight instances, named sLiSCP-light-[192] and sLiSCP-light-[256], with state sizes 192 and 256 bits, respectively. Table 2.2 presents the recommended parameters for two lightweight instances of the sLiSCP-light permutation.

<table>
<thead>
<tr>
<th>Permutation</th>
<th>m</th>
<th>Rounds</th>
<th>Steps</th>
<th>Total # rounds $(u \cdot s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>sLiSCP-light-[192]</td>
<td>24</td>
<td>6</td>
<td>18</td>
<td>108</td>
</tr>
<tr>
<td>sLiSCP-light-[256]</td>
<td>32</td>
<td>8</td>
<td>18</td>
<td>144</td>
</tr>
</tbody>
</table>

2.3.3 sLiSCP-light constants

As depicted in Figure 2.2, the step function of sLiSCP-light is parametrized by two sets of constants $(rc^i_0, rc^i_1)$ and $(sc^i_0, sc^i_1)$. We call them round and step constants, respectively. The round constants are used within the Simeck boxes while step constants are XORed to the even
subblocks as described earlier. In Table 2.3 and 2.4, we list the hexadecimal values of constants for both the instances of sLiSCP-light. More details on how to generate these constants can be found in [3, 4, 5].

Table 2.3: Round and step constants for sLiSCP-light-[192]

<table>
<thead>
<tr>
<th>step $i$</th>
<th>$(r_{c0}^i, r_{c1}^i)$</th>
<th>$(s_{c0}^i, s_{c1}^i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>(7, 27), (4, 34), (6, 20), (25, 19), (17, 35), (1c, f)</td>
<td>(8, 29), (c, 1d), (a, 33), (2f, 2a), (38, 1f), (24, 10)</td>
</tr>
<tr>
<td>6 - 11</td>
<td>(12, 8), (3b, c), (26, a), (15, 2f), (3f, 38), (20, 24)</td>
<td>(36, 18), (d, 14), (2b, 1e), (3e, 31), (1, 9), (21, 2d)</td>
</tr>
<tr>
<td>12 - 17</td>
<td>(30, 36), (28, d), (3c, 2b), (22, 3e), (13, 1), (1a, 21)</td>
<td>(11, 1b), (39, 16), (5, 3d), (27, 3), (34, 2), (2e, 23)</td>
</tr>
</tbody>
</table>

Table 2.4: Round and step constants for sLiSCP-light-[256]

<table>
<thead>
<tr>
<th>step $i$</th>
<th>$(r_{c0}^i, r_{c1}^i)$</th>
<th>$(s_{c0}^i, s_{c1}^i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>(f, 47), (4, b2), (43, b5), (f1, 37), (44, 96), (73, ee)</td>
<td>(8, 64), (86, 6b), (e2, 6f), (89, 2c), (e6, dd), (ca, 99)</td>
</tr>
<tr>
<td>6 - 11</td>
<td>(e5, 4c), (b, f5), (47, 7), (b2, 82), (b5, a1), (37, 78)</td>
<td>(17, ea), (8e, 0f), (64, 04), (6b, 43), (6f, f1), (2c, 44)</td>
</tr>
<tr>
<td>12 - 17</td>
<td>(96, a2), (ee, b9), (4c, f2), (f5, 85), (7, 23), (82, d9)</td>
<td>(dd, 73), (99, e5), (ea, 0b), (0f, 47), (04, b2), (43, b5)</td>
</tr>
</tbody>
</table>

2.4 Recommended Instantiations

We instantiate SpoC with sLiSCP-light permutation to provide two lightweight AEAD instances which offer 128-bit security. Table 2.5 presents the recommended parameter sets for two lightweight instances of SpoC. The list is sorted in priority, i.e., SpoC-64_sLiSCP-light-[192] is the primary recommendation and SpoC-128_sLiSCP-light-[256] is the secondary one.

Table 2.5: Recommended parameter sets of SpoC

<table>
<thead>
<tr>
<th>Instance</th>
<th>$b$</th>
<th>$r$</th>
<th>$\kappa$</th>
<th>$n$</th>
<th>$t$</th>
<th>Data (in bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SpoC-64_sLiSCP-light-[192]</td>
<td>192</td>
<td>64</td>
<td>128</td>
<td>128</td>
<td>64</td>
<td>$2^{50}$</td>
</tr>
<tr>
<td>SpoC-128_sLiSCP-light-[256]</td>
<td>256</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>$2^{50}$</td>
</tr>
</tbody>
</table>

2.5 Positions of Rate and Capacity

In this section, we illustrate the exact positions of the state which are used for $r$-bit keystream and for masking $r$-bit capacity. We view each subblock of sLiSCP-light state as a sequence of bytes, i.e., $S_i = S_i[0]||\cdots||S_i[j]$ where $0 \leq i \leq 3$ and $j = 5$ (resp. 7) for sLiSCP-light-[192] (resp. sLiSCP-light-[256]). Similarly, we write $Y$ and $Z$. The rate and masked capacity byte positions of SpoC-64_sLiSCP-light-[192] are given by:

rate: $S_0[0], S_0[1], S_0[2], S_0[3], S_2[0], S_2[1], S_2[2], S_2[3]$

masked capacity: $S_1[0], S_1[1], S_1[2], S_1[3], S_3[0], S_3[1], S_3[2], S_3[3]$.

For SpoC-128_sLiSCP-light-[256], even (resp. odd) indexed sub-blocks constitute the rate (resp. masked capacity) part of the state. Figure 2.4 depicts the above positions for both instances of SpoC and 1-1 correspondence between SpoC and sLiSCP-light state.
2.6 Loading Key and Nonce

In this section, we describe the postions where the 128-bit key \(K = K_0||K_1\) and 128-bit nonce \(N = N_0||N_1\) are loaded in the state. In particular, we define the functions \(\text{load-SpoC-128}(N, K)\) and \(\text{load-SpoC-64}(N_0, K)\).

For \(\text{SpoC-128}\_s\_\text{LiSCP-light-}[256]\) we load the key and nonce in odd and even subblocks, respectively. Formally, on calling \(\text{load-SpoC-128}(N, K)\), the state is loaded as follows.

\[
S_1[j] \leftarrow K_0[j]; S_3[j] \leftarrow K_1[j]; S_0[j] \leftarrow N_0[j] \text{ and } S_2[j] \leftarrow N_1[j], \text{ for } 0 \leq j \leq 7.
\]

The \(\text{load-SpoC-64}(N_0, K)\) function for \(\text{SpoC-64}\_s\_\text{LiSCP-light-}[128]\) is given by:

\[
S_1[0], \ldots, S_1[5] \leftarrow K_0[0], \ldots, K_0[5] \\
S_2[0], \ldots, S_2[5] \leftarrow K_1[0], \ldots, K_1[5] \\
S_0[0], \ldots, S_0[3] \leftarrow N_0[0], \ldots, N_0[3] \\
S_2[0], \ldots, S_2[3] \leftarrow N_0[4], \ldots, N_0[7] \\
S_0[4], S_0[5] \leftarrow K_0[6], K_0[7] \\
S_2[4], S_2[5] \leftarrow K_1[6], K_1[7].
\]

2.7 Tag Generation

In this section, we show the procedure to compute the tag for \(\text{SpoC-64}\_s\_\text{LiSCP-light-}[192]\) and \(\text{SpoC-128}\_s\_\text{LiSCP-light-}[256]\). We denote this process by \(\text{tagextract-SpoC-r}\) for \(r \in \{64, 128\}\).

For \(\text{SpoC-128}\_s\_\text{LiSCP-light-}[256]\), the \(\text{tagextract-SpoC-128}\) function computes the 128-bit tag \(T = T_0||T_1\) which is given by \(T_0 \leftarrow S_1\) and \(T_1 \leftarrow S_3\). Similarly, \(\text{tagextract-SpoC-64}\) computes the 64-bit tag \(T\) of \(\text{SpoC-64}\_s\_\text{LiSCP-light-}[192]\) as follows.

\[
T[0], \ldots, T[3] \leftarrow S_1[0], \ldots, S_1[3] \\
T[4], \ldots, T[7] \leftarrow S_3[0], \ldots, S_3[3].
\]
Chapter 3

Security Claims

In Table 3.1, we list the security levels of two instances of SpoC. We assume a nonce-respecting adversary, i.e., for a fixed key, the public nonce value is never repeated for an encryption query. Moreover, the numbers are based on our security analysis of sLiSCP-light permutation which is indistinguishable from a random permutation for 18 steps. Accordingly, we do not claim security for SpoC with round-reduced sLiSCP-light permutation.

Table 3.1: Security levels of the two AEAD algorithms based on SpoC using sLiSCP-light permutation. The advantage values indicate the best possible attack advantage, when the prescribed data and time limit is achieved.

<table>
<thead>
<tr>
<th>AEAD algorithm</th>
<th>Confidentiality</th>
<th>Integrity</th>
<th>Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time (in bytes)</td>
<td>Data (in bytes)</td>
<td></td>
</tr>
<tr>
<td>SpoC-64_sLiSCP-light[192]</td>
<td>$2^{112}$</td>
<td>$2^{50}$</td>
<td>$2^{112}$</td>
</tr>
<tr>
<td>SpoC-128_sLiSCP-light[256]</td>
<td>$2^{112}$</td>
<td>$2^{50}$</td>
<td>$2^{112}$</td>
</tr>
</tbody>
</table>

Table 3.1: Security levels of the two AEAD algorithms based on SpoC using sLiSCP-light permutation. The advantage values indicate the best possible attack advantage, when the prescribed data and time limit is achieved.
Chapter 4

Security Analysis

4.1 Security of SpoC

In this section, we present the security analysis of SpoC against generic attacks (assuming the underlying permutation is ideal, i.e., random permutation). First, we briefly explain possible attack strategies along with a rough lower bound estimate on the amount of data and time complexity required for each attack. Then, we substitute concrete parameters and compute the actual advantage to validate the recommended criteria listed in Table 3.1.

In the following discussion:

- $D$ denotes the data complexity (or online queries). This parameter quantifies the online resource requirements, and includes the total number of blocks (among all messages and associated data) processed through the underlying permutation for a fixed key. For simplicity we also use $D$ to account for the data complexity of forging attempts.

- $T$ denotes the time complexity (or offline queries). This parameter quantifies the offline resource requirements, and includes the total time required to process the offline evaluations of the underlying permutation. Since one call of the permutation can be assumed to take a constant amount of time, we generally take $T$ as the total number of offline calls to the permutation.

4.1.1 Key or internal state recovery

Key recovery. The adversary can try to guess the key using offline permutation queries. Once the key is known, the adversary can certainly distinguish, forge valid ciphertexts, or worse recover the plaintext. But, since the key is chosen uniformly in both SpoC-64 and SpoC-128, this strategy would require exhaustive search over the key space, i.e., $T \approx 2^c$ many offline queries, and a constant number of online queries, i.e., $D = O(1)$, to filter out the correct key.

State recovery. The adversary can try to guess the internal state for some encrypted block using a combination of offline and online queries. If the adversary guesses the state correctly then it can forge valid ciphertexts for the nonce value used in this encrypted block. In fact, given one internal state, the adversary can even recover the key. We show here that the internal state recovery is much harder than standalone key recovery. Recall that we denote the internal state by the tuple $(Y, Z)$. Note that guessing just one of $Y$ or $Z$ is not enough as the other value is random. Further, guessing both $Y$ and $Z$ requires the product of data and time, $DT \approx 2^b$.

This can be argued using list matching attack, i.e., the adversary creates a list $L_T$ of $T$ offline query-response tuples and a list $L_D$ of $D$ online query-response tuples (with one block PT). A matching between $L_T$ and $L_D$ happens with approx. $DT \cdot 2^{-b}$ probability. So, to get a non negligible advantage, one must satisfy $DT \approx 2^b$. 

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4.1.2 Privacy of SpoC

In privacy attacks the adversary is concerned with distinguishing the SpoC mode with an ideal authenticated encryption scheme. In addition to access of the encryption algorithm, the adversary is also allowed offline evaluations of the underlying permutation. A trivial attack strategy is guessing the key or internal state (as discussed in Section 4.1.1). Non-trivially, the adversary can distinguish the mode from ideal if there is no randomness in some ciphertext (or tag) blocks. This is possible in the following two ways:

1. **Online-online block matching.** For a pair of distinct online (in this case encryption) query blocks, the internal state matches. Then, the block that appears later will have non-random behavior. Note that this matching is only accidental and will happen with probability approx. $2^{-b}$ in both SpoC-64 and SpoC-128. Thus, it requires $D^2 \approx 2^b$.

2. **Online-offline block matching.** This is similar to the state recovery attack strategy of Section 4.1.1. Again this matching will happen accidentally with probability approx. $2^{-b}$, which gives $DT \approx 2^b$.

4.1.3 Integrity of SpoC

Integrity violation means that the adversary can forge a new and valid (passes verification) ciphertext and tag pair. The adversary is allowed to make encryption queries to the encryption algorithm and forging queries to the decryption algorithm.

In a forgery attack, the adversary can apply previous strategies of key or state recovery as in Section 4.1.1. Other attack strategies are described below:

1. **Tag guessing.** This is a more direct attack, where the adversary makes arbitrary decryption attempts in the hope that the tag matches. This is equivalent to guessing $r$-bit output of a random permutation, which holds with approx. $2^{-r}$ probability for each query. So tag guessing attack would require $D \approx 2^r$.

2. **Decryption query matching with online chain.** This corresponds to the attack strategy where the adversary tries to match full state of some decryption query block to some previous encryption query block. This may lead to a forgery in the following manner:
Suppose the adversary gets the response $(c_1', c_2', c_3', c_4', c_5', t')$ for some encryption query, and then tries a decryption query of the form $(c_1, c_2, c_3, c_4', c_5, t')$ (with a different nonce). In this case the adversary forges with certainty, if the next internal state corresponding to $c_3$ of encryption query matches with the one corresponding to $c_3'$ of encryption query. One can show that the probability of such event for all decryption query blocks is approx. $rD^2/2^b + D/2^{2r}$, which gives $D \approx \min(\sqrt{2^{b-\log_2 r}}, 2^{2r})$.

3. **Decryption query matching with offline chain.** This corresponds to the attack strategy where the adversary tries to create a valid forgery using offline queries. This would mean that the adversary constructed a chain of internal states (for some fixed ciphertext blocks followed by a fixed tag value) using offline queries and then matched some decryption query to such a chain. The chain can be constructed by making permutation queries in one of the two ways:

- **Using forward only or backward only queries.** This corresponds to the event where the chain is created using forward only or backward only queries. In this case, the probability of successful forgery can be bounded by approx. $rDT/2^b + T/2^r$.
• Using both forward and backward queries. This corresponds to meet-in-the-middle kind of attack where the chain is created using both forward and backward calls to the permutation. In this case, the probability of successful forgery can be bounded by approx. $\frac{cDT^2}{2^{b+c}} + \frac{T^2}{2^{2c}}$.

On combining the two cases, we get $DT \approx \min(2^{b-\log_2 r}, 2^{b-\log_2 c})$ and $T \approx 2^c$.

4.1.4 Validation of security claims

The security claims given in Table 3.1 follow from the rough lower bounds on $D$, $T$, and $DT$, as discussed in sub sections 4.1.1-4.1.3. Specifically, putting $D \leq 2^{50}$ bytes and $T \leq 2^{112}$, gives a dominating term of at most $2^{-16}$ for both SpoC-64 and SpoC-128, which corresponds to the key recovery advantage. In other words, within the recommended resource limits and assuming that the underlying permutation is close to ideal, the most potent attacks against SpoC-64 and SpoC-128 are key recovery attacks.

4.2 Security of sLiSCP-light

In what follows, we present the results of our cryptanalysis of the two instances of sLiSCP-light permutation. Since the permutation is used in SpoC, we aim to provide evidence of how it is secure against various distinguishing attacks in an attempt to prove that its behavior is as close as possible to that of an ideal permutation. Our analysis focuses on providing results related to the diffusion, differential and linear, algebraic degree, self-symmetry properties of the permutation.

4.2.1 Diffusion

We investigate the following two properties to asses the diffusion behavior of sLiSCP-light. For the details and results of the adopted methodologies, the reader is referred to [4].

1. Permutation full bit diffusion. We evaluate the minimum number of steps required such that each bit in the state depends on all the input state bits. We find that using 6 (resp. 8) rounds of Simeck in sLiSCP-light-[192] (resp. sLiSCP-light-[256]), full bit diffusion is achieved after four steps.

2. Avalanche effect. We use a uniform random sampling method to evaluate the average number of flipped bits after four steps corresponding to flipping one bit in the input state. More precisely, for each bit position in the input state, we generate 1024 random input states and flip this bit once and count the number of changed bits in the output state. Then we compute the average number of changes per bit over these 1024 random samples. We found that the average numbers of flipped bits after 4 steps corresponding to flipping the individual 192 (resp. 256) bit positions for sLiSCP-light-[192] (resp. sLiSCP-light-[256]) spans between 95.13 and 96.56 (resp. 126.98 and 128.90).

Based on the above results, we claim that meet/miss-in-the-middle distinguishers may not cover more than eight steps because eight steps guarantee full bit diffusion in both the forward and backward directions.
4.2.2 Differential and linear cryptanalysis

In order to evaluate the differential and linear behavior of sLiSCP-light, we firstly give our results of analyzing the differential and linear properties of the Simeck boxes. Such results are generated using the SAT/SMT tools proposed in [13] coupled with an optimized differentials and linear masks exhaustive search. Secondly, we develop a MILP model for the sLiSCP-light permutation to bound the minimum number of differentially and linearly active Simeck boxes in order to evaluate the expected maximum probabilities of differential and linear characteristics.

**Differential analysis of Simeck box.** Generally, one may derive estimates for the expected Maximum Differential Probabilities (MDP) and maximum linear squared correlation (MLSC) of Simeck boxes by adopting the Markov assumption, hence ignoring the effect of the constants similar to keyed ciphers (cf. Sec. 5.1 in [3]). Tighter estimates for the MDP of the constant-based Simeck boxes can be obtained by considering the differential effect along with an exhaustive search for the exact probabilities associated with the expected optimal differentials as has been shown in [4].

**Expected maximum probabilities of differential and linear characteristics.** According to our diffusion and ideal permutation criteria, we wanted to find the optimal number of rounds, $u$, for $\text{SB}_b^{48}$ and $\text{SB}_u^{64}$ boxes so that we achieve the expected ideal differential and linear behavior in the minimum number of steps, $s$. Additionally, we constrained the lower bound on $s$ such that we run the permutation for at least three times the number of steps required for full bit diffusion. Such analysis has been carried out simultaneously with bounding the minimum number of active Simeck boxes in order to evaluate the trade off between the number of Simeck rounds, $u$, and permutation steps, $s$. More formally, for a Simeck box that is iterated for $u$ rounds, let $\delta$ and $\gamma$ denote the $\log_2$ scaled MDP and MLSC, respectively. Given an $s$-step iterated $b$-state sLiSCP-light permutation, let $m_s$ be the minimum number of active Simeck boxes and $d_s$ denote the number of steps required to achieve full bit diffusion. Then we require the following three conditions to hold:

1. The maximum expected differential characteristic probability (MEDCP) and the maximum expected linear characteristic squared correlation (MELCSC) to be upper bounded by $2^{-b}$ and $2^{-b/2}$, respectively. Formally, $\delta m_s \leq -b$ and $\gamma m_s \leq -b/2$.

2. The total number of steps to be lower bounded by three times the number of steps required for full bit diffusion. Formally, $s \geq d_s$.

3. The total number of rounds, $u \times s$ in the permutation is minimized as this directly translates to better performance.

In [4], the trade-offs between $u$ and $s$ are considered and it has been found that for $\text{SB}_u^{48}$ (resp. $\text{SB}_u^{64}$), $u = 6$ (resp. $u = 8$), $\delta = -10.7$ (resp. $\delta = -15.9$), $\gamma = -10.8$ (resp. $\gamma = -15.6$) the above three conditions are optimally satisfied when $s = 18$ and accordingly $m_s = 18$. In other words, the expected bounds on the MEDCP and MELCSC are as follows:

\[
\begin{align*}
\text{sLiSCP-light-[192]}: & \quad (\text{MDP}(\text{SB}_6^{48}))^{18} = (2^{-10.7})^{18} = 2^{-192.6} \\
& \quad (\text{MLSC}(\text{SB}_6^{48}))^{18} = (2^{-10.8})^{18} = 2^{-194.4} \\
\text{sLiSCP-light-[256]}: & \quad (\text{MDP}(\text{SB}_8^{64}))^{18} = (2^{-15.9})^{18} = 2^{-286.2} \\
& \quad (\text{MLSC}(\text{SB}_8^{64}))^{18} = (2^{-15.6})^{18} = 2^{-280.8}.
\end{align*}
\]

4.2.3 Algebraic distinguishers

The algebraic degree of sLiSCP-light can be upper bounded using a tweaked version of the division property that is employed to find the degree of an $s$-step sLiSCP-light permutation [16,
In [4], it is found that the algebraic degree of $SB_{6}^{48}$ (resp. $SB_{8}^{64}$) is 19 (resp. 36) which results in an upper bound on the algebraic degree of all component functions of sLiSCP-light-[192] (resp. sLiSCP-light-[256]) of 189 (resp. 247) after only 5 (resp. 4) steps. Such numbers suggest that maximum degree for sLiSCP-light-[192] (resp. sLiSCP-light-[256]) maybe reached after 7 (resp. 6) steps of the permutation. In what follows, we give the results of our integral and zero-sum distinguishers.

**Integral distinguishers.** According to the cryptanalysis presented in [4], we report that for both instances of sLiSCP-light, there exists an 8-step integral distinguishers that can be found with data and time complexities of $2^{b-1}$.

**Zero-sum distinguishers.** It is found that the maximum number of steps covered by zero-sum distinguishers in one direction is at most 7 [4]. Thus following a start from the middle approach, a 14-step zero-sum distinguisher exists for sLiSCP-light-[192] (resp. sLiSCP-light-[256]). Such a distinguisher require data and time complexities equal to that of the exhaustive search.

### 4.2.4 Rotational, slide and invariant subspace distinguishers

A cryptographic permutation where the internal steps can not be distinguished can exhibit undesired self-symmetry properties. To thwart such properties in sLiSCP-light-[192] (resp. sLiSCP-light-[256]), we employ a 6-bit (resp. 7-bit) LFSR to generate a tuple of two round constants $(rc_0^i, rc_1^i)$, and a tuple of two step constants, $(sc_0^i, sc_1^i)$ (see Chapter 2 for details). In order to mitigate rotational, slide, and invariant subspace distinguishers, we ensure that the following conditions hold:

- For $0 \leq i \leq 17$, $sc_0^i \neq sc_1^i$
- For $0 \leq i \leq 17$, $(rc_0^i, rc_1^i) \neq (sc_0^i, sc_1^i)$
- For $0 \leq i, j \leq 17$ and $i \neq j$, $(rc_0^i, rc_1^i) \neq (rc_0^j, rc_1^j)$
- For $0 \leq i, j \leq 17$ and $i \neq j$, $(sc_0^i, sc_1^i) \neq (sc_0^j, sc_1^j)$.  

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Chapter 5

Design Rationale

5.1 Novelty of SpoC

The design of SpoC is inspired by the Beetle mode of operation which offers better security as compared to the traditional Sponge duplex mode. Our goal is to achieve better security and smaller state size than both Sponge duplex and Beetle, while keeping the overheads as low as possible. We achieve this goal by simply masking the capacity of the permutation state with the input AD/PT block. This is quite different from Sponge duplex and Beetle, where instead of capacity, rate is masked by input. In the decryption phase of Sponge duplex the input rate bits of any permutation call is completely controlled by the adversary, as the input rate bits are same as the ciphertext bits, which leads to a loss in security. SpoC avoids such security loss by masking the capacity instead of the rate bits.

In summary, the capacity masking helps SpoC in achieving significantly higher security for a smaller state size, as compared to both Sponge duplex and Beetle (see Section 4.1). For instance among the three modes, only SpoC achieves significant security up to data complexity of $\approx 2^{60}$ blocks and time complexity of $\approx 2^{120}$, when instantiated with a 192-bit permutation. SpoC also has some advantages over Beetle’s internal state update function in terms of XOR counts per block and some minor shift operations.

5.2 Choice of the Permutation: sLiSCP-light

Our goal is to choose a permutation which, to the best of our knowledge, offers the lowest hardware footprint for SpoC. Although, SpoC has higher security than traditional Sponge duplex and Beetle mode of operation, it still requires an extra $r$-bit XORs and $r$-bit MUXs for the Z part of state. Thus, to have an overall lightweight AEAD scheme, permutation alone should be lightweight.

Our choice of $\Pi$, i.e., $\Pi := s\text{LiSCP-light}-[b]$ for $b \in \{192, 256\}$ has the lowest hardware footprint among all other permutations of similar state sizes [4]. It adopts two of the well analyzed cryptographic primitives in literature, namely (tweaked) Type II Generalized Feistel Structure and round-reduced unkeyed Simeck block cipher as its components. In addition, it has a simple security analysis and offers good bounds against the generic distinguishers (see Section 4.2).

5.3 Choice of Rate and Capacity Positions

The choice of rate and capacity positions for SpoC depends on the underlying permutation. Since, we instantiate SpoC with sLiSCP-light permutation, we have followed a similar strategy
in choosing the rate and capacity positions as the one that has been used in sLiSCP [3]. The data block to be processed is absorbed in the odd subblocks and keystream is taken from the even indexed subblocks (see Section 2.5 for exact byte positions). Such capacity positions allow the input bits to be processed by the Simeck sboxes as soon as possible so we achieve faster diffusion. Also, our choice forces any injected difference to activate Simeck sboxes in the first step which also enhances sLiSCP-light’s resistance to differential and linear cryptanalysis. This observation has also been confirmed by a third party cryptanalysis of sLiSCP [14].

5.4 Statement

The authors declare that there are no hidden weaknesses in SpoC-64_sLiSCP-light-[192] and SpoC-128_sLiSCP-light-[256].
Chapter 6

Hardware Implementation

In this chapter, we provide the details of our ASIC implementation of sLiSCP-light-192, sLiSCP-light-256 permutations and SpoC-64, we also estimate that of SpoC-128. The reported implementations in ASIC CMOS 65nm and 130nm technologies.

6.1 ASIC Implementation

SpoC is highly hardware optimized and has a very efficient ASIC implementations particularly because its core permutation sLiSCP-light employs partial layers. More precisely, the $\text{SB}^{2m}_u$ boxes, step constant addition, and linear mixing are all applied on half of the state. Additionally, each $\text{SB}^{2m}_u$ box is itself a very efficient unkeyed Feistel round function. The datapath of the round-based ASIC parallel architecture implementation of a given sLiSCP-light instance is depicted in Figure 6.1.

The implementations of both sLiSCP-light and SpoC in ASIC are carried out using STMicroelectronics CMOS 65nm CORE65LPLVT library and IBM CMOS 130nm library. As depicted in Table 6.1, the parallel implementations in CMOS 65nm show that the area of sLiSCP-light-192 (resp. sLiSCP-light-256) is 1820 (resp. 2397) GE. Their areas in CMOS 130nm are 1892 GE and 2500 GE, respectively. Throughput is calculated by $\frac{b}{\text{latency}} \times 100$, where $b$ denotes the state size and latency denotes the number of clock cycles for one permutation call and is equal to the total number of permutation rounds, $s \times u$. 
Table 6.1: Parallel hardware implementation results of sLiSCP-light-192 and sLiSCP-light-256. Throughput and power are given at a frequency of 100 kHz.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>sLiSCP-light-192</td>
<td>65 130</td>
<td>108</td>
<td>1820</td>
<td>3.97</td>
<td>177.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1892</td>
<td>5.05</td>
<td></td>
</tr>
<tr>
<td>sLiSCP-light-256</td>
<td>65 130</td>
<td>144</td>
<td>2397</td>
<td>4.77</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2500</td>
<td>7.27</td>
<td></td>
</tr>
</tbody>
</table>

Design flow and metrics. The Synopsys Design Compiler Version D-2010.03-SP4 is used to synthesize the RTL of the designs into netlist based on the STMicroelectronics CMOS 65nm CORE65LPLVT_1.20V and IBM CMOS 130nm CMR8SF-LPVT Process SAGE v2.0 standard cell libraries with both having a typical 1.2V voltage. Cadence SoC Encounter v09.12-s159 is used to finalize the place and route phase in order to generate the layout of the designs. We use Mentor Graphics ModelSim SE 10.1a to conduct functional simulation of the designs and perform timing simulation by using the timing delay information generated from SoC Encounter. We provide the areas and power consumption of both sLiSCP-light instances and SpoC after the logic synthesis.

We determine the power consumption based on the activity information generated from the timing simulation with a frequency of 100 kHz, and a duration time of 0.1s using SoC Encounter v09.12-s159_1. We specifically use 100 kHz clock frequency because it is widely used for benchmarking purpose in resource constrained applications and 0.1 s is long enough to provide an accurate activity information for all the signals.

6.2 Round-based Implementation of sLiSCP-light

Our round-based implementation executes one step of the permutation in \( u \) clock cycles, where \( u = 6 \) or 8, and requires the components as given in Table 6.2. As depicted in Figure 6.1, all four \( 2m \)-bit registers are divided into two parts to accommodate the Feistel execution of the Simeck boxes. Two counters \( i \) and \( j \) of 5 and 3 bits, respectively are utilized, where \( i (0 \leq i \leq s - 1) \) controls the permutation step function and \( j (0 \leq j \leq u - 1) \) controls the round function of Simeck.

During each clock cycle when \( 0 \leq j < u - 1 \), we first XOR the right half of registers \( X_1 \) (resp. \( X_3 \)) with \( 1^{m-1}||q_j \) (resp. \( 1^{m/2-1}||q'_j \)) where \( q_j, q'_j \) are round constant bits (see Section 2.3.3). Next, the right half output of the Simeck round function (dashed box) on registers \( X_1 \) and \( X_3 \) is fed back to the left half of the registers, and the left half of the registers is shifted to the right half. When \( j \) equals \( u - 1 \), the left half of the register \( X_3 \) is replaced by the XORed value of the right half of register \( X_1 \), left half of register \( X_0 \) and \( 1^m \). At the same time, the left half of the register \( X_1 \) is XORed with the right half of the register \( X_0 \), and then is XORed with \( 1^{m-8}||s_{c_0} \).

In particular, for sLiSCP-light-192, the \( (m - 8) \) bits are first padded with two 0’s followed by padding the 6-bit constant \( s_{c_0} \). The generated new value is then shifted to the right half of the register \( X_3 \). The same process takes place between \( X_2 \) and \( X_3 \) to update the value of \( X_1 \). At the same time, the values of registers \( X_1 \) and \( X_3 \) are shifted into the registers \( X_0 \) and \( X_2 \) respectively. Multiplexers are used at the inputs of \( X_1 \) and \( X_3 \) to make a selection between the output of the Simeck boxes when \( j = u - 1 \) and the cyclically shifted registers. Finally, a new permutation step begins where \( i \) is incremented by 1 and \( j \) is reset to 0.
Table 6.2: Breakdown of the number of discrete components in both instances of sLiSCP-light, where XOR is 1-bit xor operation and MUX is 2-1 1-bit multiplexer.

<table>
<thead>
<tr>
<th>Permutation block</th>
<th>Discrete component</th>
<th>sLiSCP-light-192</th>
<th>sLiSCP-light-256</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Registers</td>
<td>4 × 48</td>
<td>4 × 64</td>
</tr>
<tr>
<td></td>
<td>MUX</td>
<td>96</td>
<td>128</td>
</tr>
<tr>
<td>$SB^2_{2u}$ boxes</td>
<td>AND</td>
<td>2 × 24</td>
<td>2 × 32</td>
</tr>
<tr>
<td></td>
<td>XOR</td>
<td>2 × 49</td>
<td>2 × 65</td>
</tr>
<tr>
<td>Step constants</td>
<td>XOR</td>
<td>2 × 6</td>
<td>2 × 8</td>
</tr>
<tr>
<td>Mix Subblocks</td>
<td>XOR</td>
<td>2 × 48</td>
<td>2 × 64</td>
</tr>
<tr>
<td>LFSR</td>
<td>Registers</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>XOR</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

6.3 SpoC Implementation Results

To implement SpoC-$r$, we implement the outer mode structure for capacity masking, plaintext/ciphertext bits and XORing 4-bit control signals, then include the sLiSCP-light-$b$ module in it. In Table 6.3, we give a numerical summary of SpoC-$r$ that covers its implementation results in CMOS 65nm and 130nm technologies, performance, and recommended parameters. Throughput in Table 6.3 is given for 1 KB messages and no associated data.

Throughput for processing an $l$-block data of length $lr$ bits and $n$-bit nonce is given by:

$$\frac{lr}{su(n/r+l)} \times 100,$$

where one permutation call is needed for initialization, one permutation call for absorbing the rest of the nonce when $n = 2r$, and $l$ calls for data authenticated encryption.

Table 6.3: Parallel hardware implementation results of SpoC-$r$. Throughput is given at a frequency of 100 kHz for processing 1 KB message with no AD.

<table>
<thead>
<tr>
<th>Instance</th>
<th>ASIC Technology</th>
<th>Parameters</th>
<th>Latency</th>
<th>Area</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[nm]</td>
<td>[cycles]</td>
<td>[GE]</td>
<td>[kbps]</td>
<td></td>
</tr>
<tr>
<td>SpoC-64</td>
<td>65 130</td>
<td>18 6 128 64 128 64</td>
<td>14040 2329</td>
<td>58.3</td>
<td></td>
</tr>
<tr>
<td>SpoC-128</td>
<td>65 130</td>
<td>18 8 128 128 128 128</td>
<td>9360 3020†</td>
<td>87.5</td>
<td></td>
</tr>
</tbody>
</table>

† Estimated area
Bibliography


Appendix A

Other NIST-LWC Submissions
Adopting sLiSCP-light Family of Permutations

In Table A.1, we list our other NIST-LWC submissions whose underlying permutation adopts a similar design as the sLiSCP-light [4] family of permutations. SpoC is an authenticated cipher that enables tighter bound on the underlying state size to offer same security as other generic AE schemes, thus allowing larger rate size. SpoC adopts sLiSCP-light-192 and sLiSCP-light-256 to enable different performance and hence different target applications. SPIX adopts sLiSCP-light in a monkey duplex to offer higher throughput than generic Sponge-based AE schemes. ACE is an all in one primitive that utilizes a generalized version of sLiSCP-light with state size 320-bit and a different linear layer to offer both hashing and authenticated encryption functionalities. In Table A.1, the submissions are classified based on their functionalities, mode of operation parameters and hardware area in ASIC CMOS 65nm technology.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Permutation</th>
<th>Functionality</th>
<th>Parameters (in bits)</th>
<th>Mode of operation</th>
<th>Area [GE]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE-256</td>
<td>sLiSCP-light</td>
<td>AEAD</td>
<td>256 64 128</td>
<td>Unified sLiSCP sponge</td>
<td>2611</td>
</tr>
<tr>
<td>ACE-64</td>
<td>sLiSCP-light-192</td>
<td>AEAD</td>
<td>192 64 128</td>
<td>SpoC</td>
<td>2329</td>
</tr>
<tr>
<td>ACE-128</td>
<td>sLiSCP-light-256</td>
<td>AEAD</td>
<td>256 128</td>
<td>SpoC</td>
<td>3020</td>
</tr>
</tbody>
</table>

Table A.1: Submissions with sLiSCP-light like permutations
Appendix B

Test Vectors

B.1 sLiSCP-light-[192]

Table B.1: Test vector for sLiSCP-light-[192] permutation

<table>
<thead>
<tr>
<th>Step</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>000000000000 000000000000 000000000000 000000000000</td>
</tr>
<tr>
<td>1</td>
<td>FFFF9AFFFFFC 0000640000D5 FFFF9FFFFFC 0000650000F4</td>
</tr>
<tr>
<td>2</td>
<td>D29A66FE8E7D C77A57FE2B66 C77A33FE2B87 D29A03FE8E8D</td>
</tr>
<tr>
<td>3</td>
<td>BB3EF980467D 663C22251B97 5EB9EE24CF23 965B6081370A</td>
</tr>
<tr>
<td>4</td>
<td>AB8B3158550D7944A50C96FAC 350C41125FA5 EF4A3727EC85</td>
</tr>
<tr>
<td>5</td>
<td>D78C6BE719475D5A8B2BCDE0 97A935C66D6A 83F8A540B3A8</td>
</tr>
<tr>
<td>6</td>
<td>A1E3DD4BB98 CF92CBD9493 A7C401B40D9 899049CC5DFB</td>
</tr>
<tr>
<td>7</td>
<td>D559023ED943CE33C62E058 64D8C2A5B999 8B4520159C3A</td>
</tr>
<tr>
<td>8</td>
<td>B5A556ECB25 E3736FA348B 7854EBA07206 9F030EAFECBC</td>
</tr>
<tr>
<td>9</td>
<td>0981F319A9B0 D068FBF3E53D 57C3E6FA6825 43DBF8989DBE</td>
</tr>
<tr>
<td>10</td>
<td>69F4002F182D B231C1D1E5B 1A0DD18272DF 9F8A0CF94DA3</td>
</tr>
<tr>
<td>11</td>
<td>DDA85151C3F3 A83794FB5D6 4C5B6323E040 4B3A3E8127DF</td>
</tr>
<tr>
<td>12</td>
<td>B667F4B427DB 32B5F61B8396 808CBDF644FB 94305A1A1B09</td>
</tr>
<tr>
<td>13</td>
<td>1863680408D2 5F6F88A84957 201C881FB27 51FB59F3B918</td>
</tr>
<tr>
<td>14</td>
<td>FE146C62788 2B34ECFB10E F4D7AB94BCAF 1988FB29936D</td>
</tr>
<tr>
<td>15</td>
<td>67711D11ECD8 74487A1BA653 7F6026E0E5C1 669A8E83956</td>
</tr>
<tr>
<td>16</td>
<td>0681098C65E7 62E55DE5568F E27A8C7A4CD 9E0FE263DDAB</td>
</tr>
<tr>
<td>17</td>
<td>AD451841DF99 D986D181F602 C4332A04432F 543BE733EEFA</td>
</tr>
<tr>
<td>18</td>
<td>2DCACA3466FA 126D47FE142 29A11A05D4C 7F702D8A764D</td>
</tr>
</tbody>
</table>

B.2 SpoC-64_sLiSCP-light-[192]

Key
Nonce
Associated data
Plaintext
Ciphertext
Tag

001111122335588DD 00111122335588DD
111122335588DD00 111122335588DD00
1122335588DD0011 1122335588DD00
335588DD00111122 335588DD001111
B11663DA2A4B955F B0499BCAB9ADGF
F447B954EF852CC1
### B.3 sLiSCP-light-[256]

Table B.2: Test vector for sLiSCP-light-[256] permutation

<table>
<thead>
<tr>
<th>Step</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000000000000000 0000000000000000 0000000000000000 0000000000000000</td>
</tr>
<tr>
<td>1</td>
<td>00000CF0000000426 FFEEF3C3FFFF3F348 00001C3C00000C2C FFFFF390FFFFFB2E</td>
</tr>
<tr>
<td>2</td>
<td>1DE1A7CF6E2DEA09 62A63FB84C7F5F233 9D59DC78B380A174 E21E5E5F91D211A9</td>
</tr>
<tr>
<td>3</td>
<td>2F11A3C5964A2121 EE5762E6E896794D 8CF14161A4E92756 CDF0FFBF5079834CA</td>
</tr>
<tr>
<td>4</td>
<td>88343AEFBA25720B 9BDD1D318AFC04E4 EEB3A3AF1EADC9E 58D666C4D390ACA3</td>
</tr>
<tr>
<td>5</td>
<td>4350BFA9D0F2156 73381560F8362948 62744930D6230A0B 349B9EF9CD6ACBB</td>
</tr>
<tr>
<td>6</td>
<td>209FDCE6B4C6E78 C94D232D517F4EB 54CF64FDCCB0179 9C3078D392CBOE7</td>
</tr>
<tr>
<td>7</td>
<td>CDF5132B02768F42 0C645033E732AA5D A754CB31E40654CE 1295300249351E2E</td>
</tr>
<tr>
<td>8</td>
<td>E3551361FF666A96 11E7A1F154C787FD 494C953F4F3E2C3C D15FFFB502EF1A5A</td>
</tr>
<tr>
<td>9</td>
<td>5BD8E9BE03B316 F11CA614E5E599A6 47AFCCD45524A4A9E 47721205E8A26E4</td>
</tr>
<tr>
<td>10</td>
<td>F197723AA428B1A2 FC546679B9B26621 4045555213693DFC 55B075EB3DF4DD</td>
</tr>
<tr>
<td>11</td>
<td>8F17F61709A800DE C96925615DB740C 72928FCB83D801 817F7D2525F4232</td>
</tr>
<tr>
<td>12</td>
<td>2B858D69E03F180C 96536EB3E32B1437 1B3E1E8EDD09B372 56B8481166EACE</td>
</tr>
<tr>
<td>13</td>
<td>32D1FCD790EF84 FE745757B23191C 1AB5B626795551D E6A88496E6EF1F55</td>
</tr>
<tr>
<td>14</td>
<td>DCEF74D18CA6AA09 60A8131451F00FD5 85E25ACD07D5A52D 1C1777F10A57AD14</td>
</tr>
<tr>
<td>15</td>
<td>4D930DEA642F22ED A3E7DE93A806267E D9FA7BA18027C58 6E8386C41776770E</td>
</tr>
<tr>
<td>16</td>
<td>40D84292E6267C2C C299B16562B93DAE E49C053B166ABF1 F2B4B0BBDB1A120</td>
</tr>
<tr>
<td>17</td>
<td>87994BD3E403B9A9E 9EB7A40050ADB69C 85D45EC423BF79F 38BEB6B23DBF958</td>
</tr>
<tr>
<td>18</td>
<td>C14FD32FD8C4F91 3D7CD37CE40CF40 47577247A907F46A B9296703C6788A4C</td>
</tr>
</tbody>
</table>

### B.4 SpoC-128_sLiSCP-light-[256]

Key
---
00111122335588DD 00111122335588DD

Nonce
---
11122335588DD00 111122335588DD00

Associated data
---
1122335588DD0011 1122335588DD00

Plaintext
---
335588DD0011112 335588DD001111

Ciphertext
---
A1F2FE57A1956C02 55C6B9B225ED39

Tag
---
745D95285F4BE3BE 99CC0ADA3EF9521B