PRINCEv2
More Security for (Almost) No Overhead

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Abstract. In this work, we propose tweaks to the `PRINCE` block cipher that help us to increase its security without changing the number of rounds or round operations. We get substantially higher security for the same complexity. From an implementation perspective, `PRINCEv2` comes at an extremely low overhead compared to `PRINCE` in all key categories, such as area, latency and energy. We expect, as it is already the case for `PRINCE`, that the new cipher `PRINCEv2` will be deployed in various settings.

Keywords: `PRINCE` · low latency · lightweight · block cipher

1 Introduction

During the last several years we have been witnessing a very rapid deployment of secure microcontrollers in IoT, automotive and cloud infrastructures. Various technology fields, including industrial automation, robotics as well as the 5th generation mobile network urge for real-time operation and require low-latency execution while preserving the highest levels of security. Low-power and low-energy requirements are of equal importance, especially when considering the IoT market where the majority of devices are in a low-power mode during most of their lifetime. Those devices occasionally wake up, carry out a quick computation, the result of which they store or communicate securely and then go back to sleep. A life most humans are craving to have.

Securing a microcontroller involves securing the following three groups of assets:

- End-user data, including dynamic data such as personal information.
- Original equipment manufacturer (OEM) intellectual property, including firmware and software.

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`https://sac2020.ca/files/preproceedings/08-PrinceV2.pdf`. The confcerence presentation is available at `https://www.youtube.com/watch?v=YBxb1oWb8OQ`.

– Silicon manufacturer intellectual property, including hardware, ROM code, crypto libraries and various drivers.

Securing each of these assets is a complex problem and requires a multi-layered approach. Starting with trust provisioning and then enabling secure boot, secure debug access, secure firmware update, secure test and life-cycle management is essential for creating a secure execution environment. One of the crucial aspects of a secure execution environment is secure storage, a security mechanism used for keeping confidentiality and integrity of valuable code and data stored on the device. Our paper focuses on memory encryption, which is a fundamental building block of secure storage.

Memory encryption has been used in the PC world for a long time already. Some examples include IBM's SecureBlue++, Intel's SGX and AMD's SEV encryption and integrity mechanisms. Those mechanisms are used to protect valuable assets against an attacker capable of monitoring and/or manipulating the memory content. The attacker is assumed to be employing various software tools running on the targeted platform as well as being able to manipulate the integrity of any underlying hardware by using invasive methods such as probing, voltage glitching, electromagnetic fault injection (EMFI), etc. While the device must remain secure in the hands of such adversary, the level of protection differs depending on whether the memory is volatile or non-volatile or whether it is internal or external to the system on chip (SoC). Securing the SoC-external memory is especially challenging while, at the same time, the advances of CMOS technology lead to increased production of FLASH-less microcontrollers. Add to this the everlasting requirement to minimize power and energy consumption as well as the never-ending race for higher performance and it will become clear why designing an efficient memory encryption scheme is a serious challenge. We are looking for a solution where a single clock cycle encryption is one cycle too many.

`PRINCE` [BCG+12] is the first publicly known low-latency family of block ciphers that got scrutinized by the cryptographic community.[7] As a result, `PRINCE` has been deployed in a number of products including LPC55S of NXP Semiconductors [NXP20], which is a family of highly constrained general purpose IoT microcontrollers.

As pointed out in [KNR12,BCG+12], the ultimate goal of low-latency block cipher design is to encrypt a block of data in a single clock cycle. The best illustration of the importance of meeting this goal is to look at the comparison of `PRINCE` and `AES` in the low-latency setting. When implemented fully unrolled, `PRINCE` occupies 4 times less silicon area while, at the same time, reaching an 8 times higher clock frequency.

Although some design principles have been explored during the design of `PRINCE`, there has been little work going on to determine the design choices that lead to the lowest-latency and most energy-efficient cipher architecture. Several parameters contribute to the efficiency of a given cipher design: area, latency, throughput, power, and energy. Several other designs, including `Midori` [BBI+15],

[7] see https://www.emsec.ruhr-uni-bochum.de/research/research_startseite/prince-challenge/

MANTIS [BJK+16] and QARMA [Ava17] have been particularly optimized for one or more of these parameters.

This document describes the result of our efforts to increase the security margins of PRINCE without significantly increasing the latency, area, power or energy consumption. We recall the PRINCE security claims as follows: an adversary who has 2^n chosen plaintext-ciphertext pairs (obtained under the same key) needs at least 2^{126-n} calls to the encryption function to recover the secret key. This security level is sufficient for most of the aforementioned applications, yet we set ourselves to explore design opportunities when facing the security requirements NIST put forward in its lightweight crypto competition [NIS]. Therefore, the targeted security level for PRINCEv2 is 112 bits [NIS18]; precisely, we claim that there is no attack against PRINCEv2 with data complexity below 2^{47} (chosen) plaintext-ciphertext pairs (obtained under the same key) and time-complexity below 2^{112}. It has to be noted that the NIST lightweight crypto competition does not focus on the design of low-latency block ciphers. Instead, it focuses on Authenticated Encryption with Associated Data (AEAD) schemes which are, in general, too slow or too big compared to dedicated block ciphers, thus failing to meet the aforementioned design challenges.

One last design constraint we put in front of ourselves is to be able to implement PRINCEv2 on top of the existing PRINCE architecture without adding a significant area overhead nor increasing the latency.

Our Contribution

Starting with the last design constraint mentioned, we tried to minimize the difference from PRINCEv2 to PRINCE. Besides minimizing the overhead of implementing one on top of the other, this has the convenient benefit that a lot of the security analysis that PRINCE received can then either directly be transferred to PRINCEv2 or transferred with small modifications.

To achieve the requested higher security level, a different key schedule is strictly necessary, as without a change there the generic bound of the FX construction applies. Through a carefully crafted and analyzed key schedule we can get a secure cipher meeting the NIST security requirements. Besides the change in the key schedule, we only add a single XOR in the middle rounds. This middle round was unkeyed in PRINCE. From an aesthetic point of view, the new key schedule has the drawback that the α-reflection property is slightly weakened. That is, decryption is not simply encryption with a modified key as in PRINCE, but requires slightly more effort.

Besides being beneficial from a security point of view, our minimal changes result in only minimal performance changes in all the aforementioned dimensions. This makes PRINCEv2, in the unrolled setting we aim at, nearly as efficient as PRINCE, while achieving a higher security level, echoing the title of our work.

We want to emphasize that the problem we are trying to solve is quite general, yet not an easy task. It touches the least understood part of block cipher design, namely the design of the key-scheduling. For an existing cipher with a potentially non-optimal key-scheduling (here PRINCE), this translates to the question on how to increase security while minimizing the resulting overhead. For the interesting – being deployed in several products – case of PRINCE, we came up with an elegant yet simple and efficient solution to this problem. This simplicity is an advantage concerning our objective. We venture to say that the smaller the change to the original PRINCE design, the higher the value of our contribution.

Outline of the Paper

We specify the design of PRINCEv2 in Section 2, highlighting the differences to PRINCE and explaining our choices in Section 3. As noted above, the main changes are in the key schedule. By not using the FX construction for this new design, we also follow the advice in [Din15].

In Section 4 we report on our findings when implementing PRINCEv2 and compare with PRINCE, Midori, MANTIS and QARMA. As we will explain there, those comparisons are naturally difficult as, for example, MANTIS and QARMA provide a tweak, which PRINCEv2 does not.

We discuss the security analysis in Section 5. As PRINCE has attracted quite some third party analysis, e.g. [CFG+14a,DZLY17,Mor17,RR16b], we can build on significant previous work. Besides confirming our belief that PRINCEv2 indeed provides the requested security level, as a side result, we derive some new insights in PRINCE as well.

2 Specification

As discussed above, we aim to keep the changes to PRINCE minimal. To achieve this, we use the same round function and only change the middle layer, key schedule and the round constants compared to PRINCE. To be self-contained, we quickly recall PRINCE's general structure and the round function, before giving the updated parts for PRINCEv2.

2.1 PRINCE

PRINCE is a family of block ciphers with block size of 64 and key size of 128 bits. The encryption function iterates the round function R five times, then applies the middle layer R', followed by five applications of the inverse round function R^{-1}. The round function itself applies an S-box layer SB, followed by a linear layer consisting of a MixColumns operation MC and a ShiftRows SR. The S-box in PRINCE family, can be chosen from one of the 8 Affine equivalent classes given in the proposal paper [BCG+12, Tab. 3]. The S-box used in the PRINCE proposal that is given in Tab. 1(a), the ShiftRows permutation applied in SR in Tab. 1(b). While the ShiftRows permutation is the same used in the AES, the MixColumns operation is built from the following four 4×4 matrices:

$$M_1 = \begin{pmatrix} 0&0&0&0 \\ 0&1&0&0 \\ 0&0&1&0 \\ 0&0&0&1 \end{pmatrix}, \quad M_2 = \begin{pmatrix} 1&0&0&0 \\ 0&0&0&0 \\ 0&0&1&0 \\ 0&0&0&1 \end{pmatrix}, \quad M_3 = \begin{pmatrix} 1&0&0&0 \\ 0&1&0&0 \\ 0&0&0&0 \\ 0&0&0&1 \end{pmatrix}, \quad M_4 = \begin{pmatrix} 1&0&0&0 \\ 0&1&0&0 \\ 0&0&1&0 \\ 0&0&0&0 \end{pmatrix},$$

Table 1. The S-box and ShiftRows permutation used in `PRINCE` and `PRINCEv2`. Note that the S-box for `PRINCE` family can be chosen from 8 Affine equivalent classes and the one given here is the one suggested in the `PRINCE` proposal paper.

(a) 4-bit S-box of `SB`

x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$S(x)$	B	F	3	2	A	C	9	1	6	7	8	0	E	5	D	4

(b) Permutation of `SR`

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	5	10	15	4	9	14	3	8	13	2	7	12	1	6	11

or in other words M_i is the 4×4 identity matrix where the ith row is replaced by the zero vector. From these M_i we build the matrices $\widehat{M}^{(0)}$, $\widehat{M}^{(1)}$ and M':

$$\widehat{M}^{(0)} = \begin{pmatrix} M_1 & M_2 & M_3 & M_4 \\ M_2 & M_3 & M_4 & M_1 \\ M_3 & M_4 & M_1 & M_2 \\ M_4 & M_1 & M_2 & M_3 \end{pmatrix}, \ \widehat{M}^{(1)} = \begin{pmatrix} M_2 & M_3 & M_4 & M_1 \\ M_3 & M_4 & M_1 & M_2 \\ M_4 & M_1 & M_2 & M_3 \\ M_1 & M_2 & M_3 & M_4 \end{pmatrix}, \ M' = \begin{pmatrix} \widehat{M}^{(0)} & 0 & 0 & 0 \\ 0 & \widehat{M}^{(1)} & 0 & 0 \\ 0 & 0 & \widehat{M}^{(1)} & 0 \\ 0 & 0 & 0 & \widehat{M}^{(0)} \end{pmatrix},$$

i.e., M' is the 64×64 block diagonal matrix with blocks $(\widehat{M}^{(0)}, \widehat{M}^{(1)}, \widehat{M}^{(1)}, \widehat{M}^{(0)})$. Finally, the `MC`-layer multiplies the state with M' and is an involution.

The round function application is interleaved with additions of the round key $\oplus_{k_i}$ and constant $\oplus_{RC_i}$, where

$$\oplus_{k_i}(x) \coloneqq x + k_i \qquad \text{and} \qquad \oplus_{RC_i}(x) = x + RC_i \ .$$

Overall for `PRINCE` we thus have the structure shown in Fig. 1 (top), where

$$R = \texttt{SR} \circ \texttt{MC} \circ \texttt{SB} \ , \quad R'_{\texttt{PRINCE}} = \texttt{SB}^{-1} \circ \texttt{MC} \circ \texttt{SB} \quad \text{and} \quad R^{-1} = \texttt{SB}^{-1} \circ \texttt{MC} \circ \texttt{SR}^{-1} \ .$$

As we modify the `PRINCE` key schedule and round constants, we do not give more details about them.

2.2 `PRINCEv2`

`PRINCEv2` is also a family of block ciphers in the same way as `PRINCE` that the applied S-box can be chosen from 8 Affine equivalent classes. For `PRINCEv2`, we keep the forward round R and backward round R^{-1} with their operations `SB`, `MC`, and `SR`. The structure for one full encryption is shown in Fig. 1 (bottom) and in full detail in Figs. 9 and 10 in the appendix.

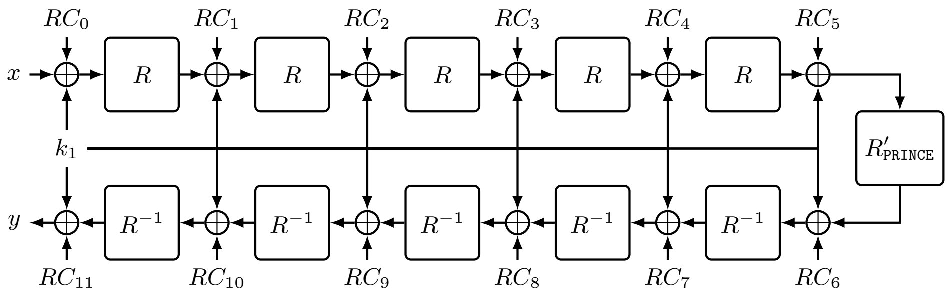
Middle Layer We change R', which was a key-less operation, to

$$R' = \texttt{SB}^{-1} \circ \oplus_{RC_{11}+k_1} \circ \texttt{MC} \circ \oplus_{k_0} \circ \texttt{SB} \ .$$

Key Schedule Given the 128-bit master key $k = (k_0 \parallel k_1)$, we define the ith round key as

$$k_i \coloneqq \begin{cases} k_0 & i \in \{0, 2, 4, 6, 8, 10\} \\ k_1 & i \in \{1, 3, 5, 7, 9, 11\} \end{cases} ,$$

that is, we alternate between the two parts of the master key k_0 and k_1.



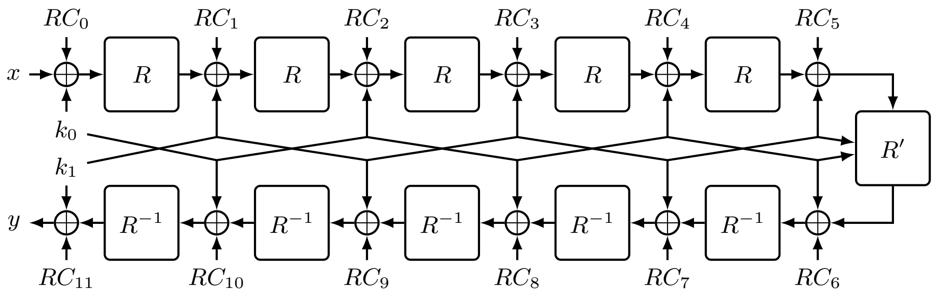


Fig. 1. (Top) `PRINCE` core structure, leaving out the FX construction; (bottom) `PRINCEv2` structure. Note that values of RC_7, RC_9 and RC_{11} in `PRINCEv2` are different than the ones in `PRINCE`.

Round Constants The round constants are derived as for `PRINCE`, but instead of adding the same α for every round constant in the second half of the encryption process ($i \geqslant 6$), we alternate adding α and β as defined in Tab. 2.

2.3 Encryption vs. Decryption

While `PRINCEv2` does not fulfil the α reflection property anymore, the choice of round keys and constants allows to implement both encryption and decryption with only a small area and delay overhead. This is shown in Fig. 10. In this figure the extra control signal **dec** switches between encryption and decryption. In particular, the `Swap` function is defined as

$$\texttt{Swap}(k_0, k_1, \text{dec}) = \begin{cases} k_0, k_1 & \text{if dec} = 0 \\ k_1 \oplus \beta, k_0 \oplus \alpha & \text{if dec} = 1 \end{cases} .$$

3 Design Rationale

The main objectives almost immediately results in clear design rationales. The first design rationale is to leave the round function, and not less important the

Table 2. Round constants used in PRINCEv2.

Constants	
RC_0 = 0000000000000000	RC_6 = 7ef84f78fd955cb1 = $RC_5 \oplus \alpha$
RC_1 = 13198a2e03707344	RC_7 = 7aacf4538d971a60 = $RC_4 \oplus \beta$
RC_2 = a4093822299f31d0	RC_8 = c882d32f25323c54 = $RC_3 \oplus \alpha$
RC_3 = 082efa98ec4e6c89	RC_9 = 9b8ded979cd838c7 = $RC_2 \oplus \beta$
RC_4 = 452821e638d01377	RC_{10} = d3b5a399ca0c2399 = $RC_1 \oplus \alpha$
RC_5 = be5466cf34e90c6c	RC_{11} = 3f84d5b5b5470917 = $RC_0 \oplus \beta$
α = c0ac29b7c97c50dd	β = 3f84d5b5b5470917

number of rounds, (almost) unchanged, and only change the key-scheduling. Note that the main reason for wanting to keep the number of round unchanged is mainly because having more rounds will necessarily increase latency and cause an overall loss in performances. As we are able to improve the security margin as in PRINCE (see Section 5), we believe that this is the correct choice to make. Here, the round-constants are thought of as part of the key-scheduling, even if it is not presented this way in the original PRINCE paper. This rationale (leaving the round function as is) both drastically simplified the design process and made it much more challenging. The simplification is due to the choices being narrowed down to a key-scheduling that has to be picked. More challenging, the analysis has to be much more precise and careful, as clearly the security margin would decrease. It is important to highlight that the security margin is relative to the claimed security level, not in absolute terms.

The only compromise from the goal of leaving the round function unchanged is the middle round. Some attacks that have been developed since the publication of PRINCE take explicit advantage of the symmetry and the key-less middle rounds. To make those attacks, particularly meet-in-the-middle attacks and accelerated exhaustive search procedures, less of a concern, it seems to be a good trade-off to spend two (actually one as will be explained in the implementation section) additional XOR on the critical path. It is noteworthy to mention that the idea of the keyed middle round is previously used in the design of QARMA block cipher.

For the key-scheduling, we were again highly restricted by the requirement of limiting the overhead of implementing decryption on top of encryption. This implies, as it did in PRINCE, that a complicated key-update is not a proper choice but a simple, up to the constants, periodic key-scheduling is best.

We opted for one of the simplest possible options: iterated round-keys.

Originally, in PRINCE, the round keys derived from the 128-bit key ($k_0 \parallel k_1$) correspond to

$$k_0 \oplus k_1 \ , \ k_1 \ , \ k_1 \ , \ k_1 \ , \ k_1 \ , \ k_1 \ , \ k_1 \oplus \alpha \ , \ k_1 \oplus \alpha \ , \ k_1 \oplus \alpha \ , \ k_1 \oplus \alpha \ , \ k_1 \oplus \alpha \ , \ k_0' \oplus k_1 \oplus \alpha \ ,$$

where k_0' is the result of a simple and efficient bijective linear mapping from k_0, and α is a constant value.

In particular, the value of k_0 is used only in the whitening keys, limiting the security generically. The α-reflection property, that is the fact that decryption is encryption with a modified key, follows as replacing k_1 by $k_1 \oplus \alpha$ reverts the order of the round keys (except for the outer whitening keys).

In PRINCEv2, using a master key $(k_0 \parallel k_1)$, we decide to choose

$$k_0\ ,\ k_1\ ,\ k_0\ ,\ k_1\ ,\ k_0\ ,\ k_1\ ,\ k_0\ ,\ k_1{\oplus}\beta\ ,\ k_0{\oplus}\alpha\ ,\ k_1{\oplus}\beta\ ,\ k_0{\oplus}\alpha\ ,\ k_1{\oplus}\beta\ ,\ k_0{\oplus}\alpha\ ,\ k_1{\oplus}\beta\ ,$$

as the round keys where α and β are constant values. The constants are chosen as digits of $\pi = 3.1415\ldots$, as they were done in PRINCE. The new constant β is simply the next in line looking at the binary digits of π, see the appendix for a sage code to reproduce the constants used. Besides, it is noteworthy to mention that due to the key additions in the middle round of PRINCEv2, it has two more round keys than the one for PRINCE.

Here, replacing k_0 by $k_1 \oplus \beta$ and k_1 by $k_0 \oplus \alpha$ does ensure that the first rounds (the first seven round keys) of the encryption circuit perform decryption as required. However, when reaching the middle round (second key addition of the middle round), an additional modification is required to ensure the second half (the second seven round keys) works as well. For the second half of the round keys, we need to XOR all of these round keys with the constant value $\alpha \oplus \beta$. While replacing k_0 by $k_1 \oplus \beta$ and k_1 by $k_0 \oplus \alpha$, needs to implement 64 multiplexers in the critical path, modifying round keys of the second half does not affect the latency. As we will show in Section 4, combining decryption together with the encryption circuit does not significantly harm performance.

The only case where this would not be necessary is when α equals β. However, this would introduce a set of weak-keys. Namely, if $k_1 \oplus k_2 = \alpha$, then encryption would equal decryption, that is, the whole cipher would be an involution.

Finally, let us explicitly state the claim we want our design to be tested against:

Security Claim: We claim that there is no attack against PRINCEv2 with data complexity below 2^{50} bytes – 2^{47} (chosen) plaintext-ciphertext pairs obtained under the same key – and time-complexity below 2^{112}. We do not claim any security in the related-key setting and related-keys have to be avoided at the protocol level.

This claim is backed up by the extensive security analysis. It is interesting to see how the advance in the state of the art has made the analysis more precise (e.g., for Boomerang-attacks using connectivity tables and for integral attacks using the division property) and simpler (using mainly MILP-based tools). Those improvements are an important tool to enable a cipher design with a very tight security claim: For a cipher optimized for low-latency, a large security margin is nothing but wasted performance.

Note that as PRINCE did not have any claim regarding security against side-channel and fault attacks, we chose to not make such claims either. Moreover to our knowledge, protecting a fully unrolled primitive against such attacks is not a well-researched area so far.

4 Implementation

The primary objective of PRINCE and PRINCEv2 is to offer low-latency single-cycle encryption and decryption. This objective requires a short critical path in round-unrolled non-pipelined hardware implementations. In other words, the ciphers aim for a small logic depth in circuit representation. Furthermore, adding decryption functionality to an encryption circuit should induce minimal area and latency overhead. PRINCE achieves this goal in part due to the so-called α-reflection property [BCG+12]. This property has been imitated by several other low-latency constructions (e.g. MANTIS [BJK+16] and QARMA [Ava17]) and mandates that decryption with one key corresponds to encryption with a related key. Due to the modified key schedule, PRINCEv2 does not fulfil the α-reflection behaviour of PRINCE. Yet, it implements a modified version that keeps the decryption overhead in hardware fairly small.

A secondary design goal is keeping its unrolled implementation cost-efficient, including a small hardware footprint (little occupied chip area) and a low energy consumption. In fact, the costs should be lower compared to unrolled implementations of other lightweight block ciphers. According to the original proposal, unrolled PRINCE with decryption and encryption capability can be clocked at frequencies up to 212.8 MHz when synthesized in NanGate 45 nm, an open-source standard cell library, and requires as little as 8260 Gate Equivalents (GE) of area [BCG+12]. PRINCEv2 aims to achieve similar performance figures while providing stronger security guarantees overall. Staying close to the initial design of PRINCE enables us to recycle and build upon the extensive security analysis it has already received. Furthermore, it allows us to construct circuits that can perform encryption and decryption in both the new PRINCEv2 *and* original PRINCE at low overhead. This provides needed legacy support and backward compatibility for a variety of applications and environments where PRINCE is already deployed.

In the following, we compare our novel PRINCEv2 design to the original PRINCE concerning the minimum latency and minimum area achieved by unrolled implementations. Since gate count and delay numbers depend on the particular technology used, we provide synthesis results from 4 different commercial standard cell libraries of feature sizes between 90 nm and 28 nm. This redundancy minimizes the influence of a single technology on the comparison's interpretation. All 4 standard cell libraries contain multiple classes of gates, namely a high threshold voltage (*hvt*) class, a standard threshold voltage (*std*) class and a low threshold voltage (*lvt*) class. These distinct classes allow to fully explore the latency-vs-leakage tradeoff. More specifically, when placing a tight constraint on the latency of a circuit, primarily *lvt* cells are chosen due to their high speed. On the other hand, when synthesizing without tight timing constraints, *hvt* cells will be chosen due to the lower energy loss through leakage currents. Using manufacturable standard cell libraries from a commercial foundry instead of open-source libraries for a design comparison is often preferable since the reported numbers are more accurate in all key categories, such as area, latency and energy. They are especially superior in power and energy estimation, as common open-source libraries fail to provide industry quality characterization in that regard. How-

Table 3. Area, latency and energy characteristics of unrolled `PRINCE` and `PRINCEv2` when constrained for minimum latency.

Techn.	**Mode**	**Cipher**	**Area** [GE]	**Latency [ns]**	**Energy** [pJ]
90 nm LP*	ENC	`PRINCE`	16244.25	**4.101177**	1.993172
		`PRINCEv2`	17661.25	**4.047311**	2.230068
	ENC/DEC	`PRINCE`	17808.00	**4.106262**	2.213275
		`PRINCEv2`	18888.75	**4.151113**	2.424250
65 nm LP*	ENC	`PRINCE`	19877.75	**2.866749**	1.602513
		`PRINCEv2`	18798.25	**2.944367**	1.492794
	ENC/DEC	`PRINCE`	19966.00	**2.946442**	1.594025
		`PRINCEv2`	21171.25	**2.930153**	1.696559
40 nm LP*	ENC	`PRINCE`	17177.00	**2.521302**	0.617719
		`PRINCEv2`	16556.50	**2.509131**	0.592155
	ENC/DEC	`PRINCE`	17377.50	**2.541220**	0.630223
		`PRINCEv2`	17799.50	**2.583466**	0.648450
28 nm HPC**	ENC	`PRINCE`	38145.33	**1.108886**	1.258586
		`PRINCEv2`	33470.33	**1.103273**	1.108789
	ENC/DEC	`PRINCE`	35297.67	**1.119593**	1.181171
		`PRINCEv2`	38962.33	**1.148693**	1.299172

* LP = Low Power
** HPC = High Performance Computing

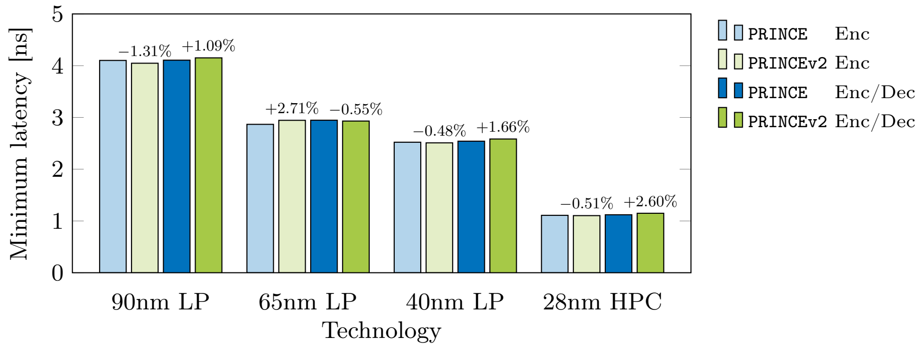


Fig. 2. Minimum achievable latency of unrolled `PRINCE` and `PRINCEv2` across different technologies.

ever, to keep our results reproducible and make comparisons to existing works easy we provide a comparison of all our unrolled `PRINCE` and `PRINCEv2` circuits to several other low-latency and low-energy constructions in NanGate 45 nm and 15 nm Open Cell Libraries (OCL) later in this section.

We consider the typical process and operating conditions in all our synthesis results, i.e., the typical PVT (process, voltage, temperature) corner case, with a nominal supply voltage and a working temperature of 25 °C. For synthesis, we

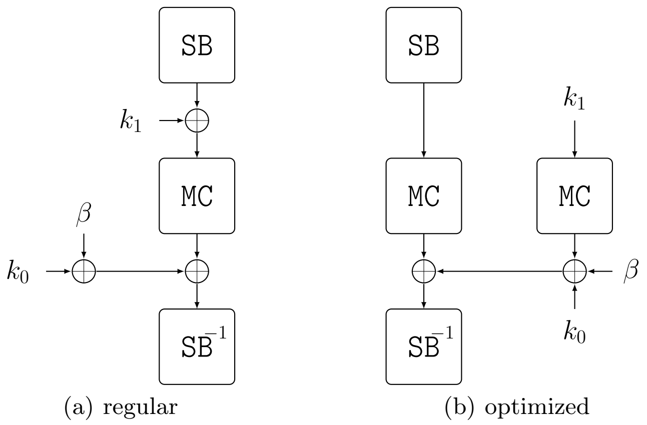


Fig. 3. Simple latency optimization strategy in the middle round of `PRINCEv2` that removes one key addition from the critical path.

have used *Synopsys Design Compiler Version O-2018.06-SP4* with three stages of the `compile_ultra` command (two incremental). As a first step, we have constrained our circuits for minimum latency. The results are given in Table 3 and visualized in Figure 2. We distinguish between circuits that can only encrypt (ENC) and circuits that can decrypt as well (ENC/DEC).

Several interesting observations can be made. Firstly, all four distinct circuits perform decidedly similar in terms of minimum latency. The difference falls in the range of single-digit picoseconds in several cases. To gain a better overview, Figure 2 provides the differences between corresponding `PRINCE` and `PRINCEv2` circuits as percentages on top of the bar graphs. Interestingly, the encryption-only version of `PRINCEv2` outperforms `PRINCE` in terms of minimum latency in three of four technologies. This may be counter-intuitive, as `PRINCEv2` adds two key additions to the middle round. However, as shown in Figure 3, those two key additions can be merged into a single one regarding the critical path by calculating and adding $\texttt{MC}(K_1)$ in parallel.

This optimization not only improves the minimum latency but also saves area.[8] One may expect the synthesis tool to perform such an optimization implicitly by itself, as two key additions and a `MC` operation in the middle essentially result in a sequence of four consecutive `XORs` per bit. Yet, our results suggest that it is indeed required to perform the optimization algorithmically in the RTL code. Additionally, it has to be noted that the original `PRINCE` design applies two key additions (whitening and round key) to the input before the first Sbox stage. `PRINCEv2`, on the other hand, applies only one. Hence, the difference between the latency of `PRINCE` and `PRINCEv2` in encryption-only mode comes down to whether the synthesizer implements the additional key `XOR` at the input more

[8] Area is saved by this optimization since slower cells with a lower drive strength can be selected for the parallel calculations. Those cells have a smaller area footprint.

efficiently or the one in the middle round. More often than not, the middle round key addition is more efficient latency-wise since the synthesizer has more freedom to move that XOR stage around (e.g., to the input, output or intermediate signals of the MC operation), while the two key XORs at the input have a fixed location and cannot be optimized beyond instantiating a three-input XOR per bit, since all inputs to the operation (key and plaintext) arrive at approximately the same time. Original PRINCE also requires an additional key XOR at the output. Yet, since the last round's output arrives much later than the keys, the key parts will be added to each other beforehand and only one of the XOR stages affects the critical path.

At this point, we should stress that differences in synthesis results of such a small magnitude may sometimes go beyond algorithmic considerations and can not always be understood in detail without having insight into the proprietary optimization algorithms used by EDA tools. Sometimes a latency optimization with a big area penalty is deemed worth it by the synthesizer, sometimes not. Thresholds for such decisions are unknown and therefore the outcome can not always be predicted. One example for such a case in Table 3 is the difference between the full variant of PRINCEv2 and its encryption-only version in 65 nm LP technology. For unknown reasons, the full variant achieves a lower latency than the encryption-only one, but at the price of a significantly increased area, indicating costly latency optimizations. However, the majority of our reported figures directly corresponds to the algorithmic differences in the analyzed ciphers and modes.

Regarding the cipher variants with decryption capability, the situation is slightly different compared to the encryption-only versions. The more complex key-multiplexing in PRINCEv2 required to choose between encryption and decryption, as apparent in Figure 10, induces additional delay. In the worst case, this results in an overhead of 2.6%, but on average the overhead is about 1.2%. Table 3 also reports area and energy numbers for the highly constrained circuits. The energy values correspond to the average energy consumed by one evaluation of the unrolled circuits at maximum clock frequency (corresponding to minimum latency). While PRINCEv2 is often more area and energy-efficient than PRINCE in encryption-only mode, PRINCEv2 with decryption capability consistently requires the largest area and consumes the most energy. Yet, the margins are still very thin. In summary, PRINCE's most important property and main selling point, namely high-speed single-cycle encryption, is well preserved by PRINCEv2. For scenarios that require no decryption but only encryption, it may even be slightly improved.

As a second step, we evaluate the minimum area that can be achieved by the unrolled circuits. In this regard, we have executed the same synthesis scripts as before, but without the tight timing constraints. Our results are reported in Table 4 and depicted as a bar graph in Figure 4.

In contrast to the latency results, a consistent overhead for minimum area can be observed for the PRINCEv2 circuits. This is expected, due to the additional operations in the middle round and the more complex key-multiplexing to decide

Table 4. Area, latency and energy characteristics of unrolled PRINCE and PRINCEv2 when constrained for minimum area.

Techn.	**Mode**	**Cipher**	**Area [GE]**	**Latency** [ns]	**Energy** [pJ]
90 nm LP*	ENC	PRINCE	**7937.50**	12.859 908	0.569694
		PRINCEv2	**8111.25**	12.856 450	0.574683
	ENC/DEC	PRINCE	**8183.00**	14.015 245	0.616671
		PRINCEv2	**8440.75**	15.513 536	0.628298
65 nm LP*	ENC	PRINCE	**8316.00**	11.434 771	0.433378
		PRINCEv2	**8385.25**	11.504 968	0.430286
	ENC/DEC	PRINCE	**8547.75**	12.349 355	0.440872
		PRINCEv2	**8792.75**	13.376 949	0.456154
40 nm LP*	ENC	PRINCE	**8563.75**	10.144 847	0.212027
		PRINCEv2	**8608.50**	10.063 908	0.207317
	ENC/DEC	PRINCE	**8780.00**	10.886 960	0.217739
		PRINCEv2	**9039.75**	11.798 657	0.226534
28 nm HPC**	ENC	PRINCE	**8197.00**	3.599 936	0.127798
		PRINCEv2	**8292.00**	3.682 593	0.127786
	ENC/DEC	PRINCE	**8426.33**	4.260 999	0.131239
		PRINCEv2	**8844.67**	4.323 993	0.134909

* LP = Low Power
** HPC = High Performance Computing

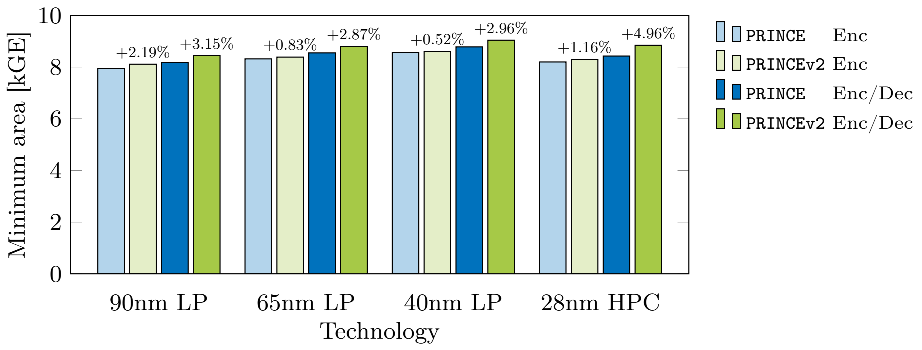


Fig. 4. Minimum achievable area of unrolled PRINCE and PRINCEv2 across different technologies.

between encryption and decryption. Yet, the average overhead is less than 1.2% for the encryption-only and less than 3.5% for the full versions. This is a rather small price to pay for the additional security PRINCEv2 provides. When comparing the low-latency and low-area implementations in Tables 3 and 4 respectively, it can be seen that area increases 2 to 4 times from low-area to low-latency constraint. Latency scales down 3 to 4 times. Energy consumption increases between 4 and 10 times, due to a dependency on both factors (caused by leakage currents). These metrics should be carefully considered when choosing operating frequency and target technology for a given application.

Finally, we compare PRINCE and PRINCEv2 to other lightweight block ciphers proposed in the literature. Only a few cryptographic primitives have made low latency a primary design objective. To the best of our knowledge, none of those who have share all design goals and security claims with PRINCE or PRINCEv2. Hence, the following comparison involves ciphers with different security and performance claims and is only supposed to put their hardware efficiency in relation to each other, without concluding the superiority of one or the other. In particular, we compare PRINCE and PRINCEv2 to the low-latency tweakable block ciphers MANTIS [BJK+16] and QARMA [Ava17]. Yet, since both of those constructions are tweakable, unlike all PRINCE versions, they can not easily achieve the same latency and area as PRINCE and PRINCEv2. We also include Midori [BBI+15] in the comparison, as the authors have partially aimed for a low logic depth as well. However, Midori primarily targets energy efficiency in round-based implementations and has no claim to provide low latency in unrolled representation. Additionally, we have developed a combination of PRINCE and PRINCEv2, which we call PRINCE+v2. This combined cipher offers a control signal to select whether the input should be processed according to the PRINCE or the PRINCEv2 specification. In environments where PRINCE is already deployed, this can be useful for backward compatibility and legacy support. We have analyzed all 6 ciphers in two modes each (ENC and ENC/DEC) in NanGate 45 nm and 15 nm Open Cell Libraries and evaluate their area-vs-latency tradeoff. The result is depicted in Figure 5 for NanGate 45 nm and in Figure 6 for 15 nm technology. The exact performance figures used to create these graphs can be found in the Appendix in Tables 5 and 6. The results in these two libraries demonstrate that PRINCE and PRINCEv2 are the most suitable choices for high-speed encryption, as long as a tweak input is not required. All PRINCE and PRINCEv2 variants outperform the other ciphers both in terms of minimum latency and minimum area. PRINCEv2 in encryption-only mode is roughly 20 percent faster than Midori and MANTIS, and 40 percent faster than QARMA. At the same time, its minimum area is about 15 percent smaller than Midori, 30 percent smaller than MANTIS and 40 percent smaller than QARMA. The results are similar when comparing both encryption and decryption implementations, except for Midori being significantly larger and slower. This outcome is unsurprising since all compared ciphers except Midori are reflection ciphers, i.e., they use a variant of the α-reflection property introduced by PRINCE. Please note that for this reason the full version of Midori64, including decryption, is barely visible in Figures 5 and 6 as it simply does not fit in the frame due to its much higher latency and area caused by the extra multiplexers required in each round. Yet the full figures for that implementation can be found in Tables 5 and 6 in the Appendix. We chose the particular instances $\texttt{MANTIS}_7$ and $\texttt{QARMA}_7$-64-σ_1 for the comparison as they are supposed to offer a similar security level as PRINCE and PRINCEv2, while being tweakable.

Table 5. Full comparison of unrolled block ciphers in NanGate 45 nm Open Cell Library.

PRINCE				PRINCEv2			
ENC		**ENC/DEC**		**ENC**		**ENC/DEC**	
Lat. [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]
4.059997	9873.33	4.119023	10486.33	4.077636	10332.00	4.245165	10780.67
4.500000	8421.67	4.500000	8807.00	4.500000	8526.67	4.500000	9488.00
5.000000	7837.00	5.000000	8213.33	5.000000	8013.00	5.000000	8659.67
5.500000	7684.33	5.500000	7959.33	5.500000	7865.67	5.500000	8328.67
6.000000	7620.00	6.000000	7874.00	6.000000	7812.33	6.000000	8196.00
6.500000	7620.00	6.500000	7868.67	6.500000	7812.33	6.500000	8144.00
7.000000	7620.00	7.000000	7868.67	7.000000	7812.33	7.000000	8141.67

PRINCE+v2				**Midori64**			
ENC		**ENC/DEC**		**ENC**		**ENC/DEC**	
Lat. [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]
4.353092	11258.33	4.469554	12395.67	4.934847	10755.67	7.111567	25058.33
4.500000	9588.33	4.500000	10709.00	4.500000	-	4.500000	-
5.000000	8622.67	5.000000	9870.33	5.000000	10353.67	5.000000	-
5.500000	8276.00	5.500000	9356.00	5.500000	9223.67	5.500000	-
6.000000	8169.67	6.000000	9091.67	6.000000	8858.00	6.000000	-
6.500000	8156.33	6.500000	8990.33	6.500000	8792.33	6.500000	-
7.000000	8155.33	7.000000	8982.00	7.000000	8748.33	7.000000	-
7.500000	8155.33	7.500000	8969.33	7.500000	8748.33	7.500000	19733.00
8.000000	8155.33	8.000000	8969.33	8.000000	8748.33	8.000000	18381.00
9.000000	8155.33	9.000000	8969.33	9.000000	8748.33	9.000000	16241.67
10.000000	8155.33	10.000000	8969.33	10.000000	8748.33	10.000000	14877.67
11.000000	8155.33	11.000000	8969.33	11.000000	8748.33	11.000000	14476.33

$\texttt{MANTIS}_7$				$\texttt{QARMA}_7$**-64-**σ_1			
ENC		**ENC/DEC**		**ENC**		**ENC/DEC**	
Lat. [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]
5.036228	14481.67	5.235198	14810.67	5.756122	17096.67	5.794558	18085.67
5.500000	12445.33	5.500000	12931.67	5.500000	-	5.500000	-
6.000000	11613.33	6.000000	12082.67	6.000000	14821.33	6.000000	15449.67
6.500000	11246.67	6.500000	11786.67	6.500000	13886.00	6.500000	14866.33
7.000000	11134.33	7.000000	11529.00	7.000000	13139.67	7.000000	14019.33
7.500000	11064.67	7.500000	11397.67	7.500000	12698.33	7.500000	13467.33
8.000000	11019.33	8.000000	11322.67	8.000000	12326.67	8.000000	13012.33
8.500000	11019.33	8.500000	11305.33	8.500000	12106.33	8.500000	12801.67
9.000000	11019.33	9.000000	11305.33	9.000000	12039.33	9.000000	12677.00
9.500000	11019.33	9.500000	11305.33	9.500000	12039.33	9.500000	12614.67
10.000000	11019.33	10.000000	11305.33	10.000000	12039.33	10.000000	12610.33
10.500000	11019.33	10.500000	11305.33	10.500000	12039.33	10.500000	12609.00

In the original proposal, the maximum achievable frequency in NanGate 45 nm of unrolled PRINCE was given as 212.8 MHz [BCG$^+$12]. Our unrolled PRINCE can be clocked at 242.8 MHz for the full variant and 246.3 MHz for the encryption-only version in the same technology, which corresponds to a 12.4% or 15.7% higher performance respectively. The minimum area was given as 8260 GE in the original proposal, while our implementations are as small as 7868.67 GE

Table 6. Full comparison of unrolled block ciphers in NanGate 15 nm Open Cell Library.

`PRINCE`				`PRINCEv2`			
ENC		**ENC/DEC**		**ENC**		**ENC/DEC**	
Lat. [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]
0.389144	13291.00	0.400530	13468.00	0.387146	13069.50	0.404112	14181.25
0.400000	12380.75	0.400000	-	0.400000	12331.75	0.400000	-
0.450000	9618.50	0.450000	10275.50	0.450000	9859.00	0.450000	11185.25
0.500000	8811.00	0.500000	9115.50	0.500000	8940.75	0.500000	9822.25
0.550000	8621.50	0.550000	8935.50	0.550000	8820.00	0.550000	9272.25
0.600000	8610.50	0.600000	8828.75	0.600000	8787.25	0.600000	9134.50
0.650000	8610.50	0.650000	8828.75	0.650000	8787.25	0.650000	9108.00
0.700000	8610.50	0.700000	8828.75	0.700000	8787.25	0.700000	9105.50
0.750000	8610.50	0.750000	8828.75	0.750000	8787.25	0.750000	9104.00

`PRINCE+v2`				**Midori64**			
ENC		**ENC/DEC**		**ENC**		**ENC/DEC**	
Lat. [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]
0.415065	14422.75	0.426661	16016.00	0.481522	13775.00	0.657338	30563.50
0.450000	11701.25	0.450000	14280.50	0.450000	-	0.450000	-
0.500000	9698.00	0.500000	11253.50	0.500000	11581.25	0.500000	-
0.550000	9234.00	0.550000	10193.00	0.550000	10427.00	0.550000	-
0.600000	9147.75	0.600000	9991.75	0.600000	9896.25	0.600000	-
0.650000	9163.00	0.650000	9967.25	0.650000	9831.00	0.650000	-
0.700000	9144.00	0.700000	9931.75	0.700000	9806.50	0.700000	28135.25
0.750000	9143.50	0.750000	9931.25	0.750000	9806.50	0.750000	22886.75
0.800000	9143.50	0.800000	9929.75	0.800000	9806.50	0.800000	20793.75
0.850000	9143.50	0.850000	9929.00	0.850000	9806.50	0.850000	18871.75
0.900000	9143.50	0.900000	9929.00	0.900000	9806.50	0.900000	17772.00
1.000000	9143.50	1.000000	9929.00	1.000000	9806.50	1.000000	16423.00
1.100000	9143.50	1.100000	9929.00	1.100000	9806.50	1.100000	15420.75
1.200000	9143.50	1.200000	9929.00	1.200000	9806.50	1.200000	15380.00
1.300000	9143.50	1.300000	9929.00	1.300000	9806.50	1.300000	15318.00

`MANTIS`$_7$				`QARMA`$_7$**-64-**σ_1			
ENC		**ENC/DEC**		**ENC**		**ENC/DEC**	
Lat. [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]	**Lat.** [ns]	**Area** [GE]
0.492660	17542.75	0.504465	18193.75	0.542777	20736.25	0.552887	22130.75
0.500000	17142.75	0.500000	-	0.500000	-	0.500000	-
0.550000	14404.00	0.550000	15159.25	0.550000	20736.25	0.550000	-
0.600000	13650.00	0.600000	14464.50	0.600000	16413.25	0.600000	18195.25
0.650000	12469.00	0.650000	12804.75	0.650000	14864.25	0.650000	16299.75
0.700000	12378.25	0.700000	12681.50	0.700000	13862.00	0.700000	15111.25
0.750000	12285.75	0.750000	12626.75	0.750000	13794.00	0.750000	14542.25
0.800000	12275.00	0.800000	12580.00	0.800000	13531.25	0.800000	14292.25
0.850000	12275.00	0.850000	12565.00	0.850000	13359.00	0.850000	14130.25
0.900000	12275.00	0.900000	12561.25	0.900000	13304.00	0.900000	14009.75
0.950000	12275.00	0.950000	12561.25	0.950000	13304.00	0.950000	13988.75

for the full variant and 7620.00 GE for the encryption-only version. That corresponds to a 5.0% or 8.4% higher area efficiency respectively. We conclude that

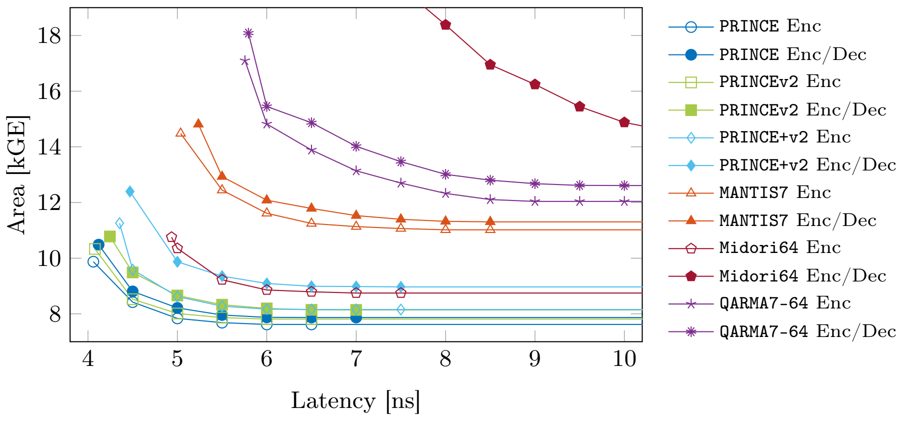


Fig. 5. Comparison of unrolled block ciphers in NanGate 45 nm Open Cell Library.

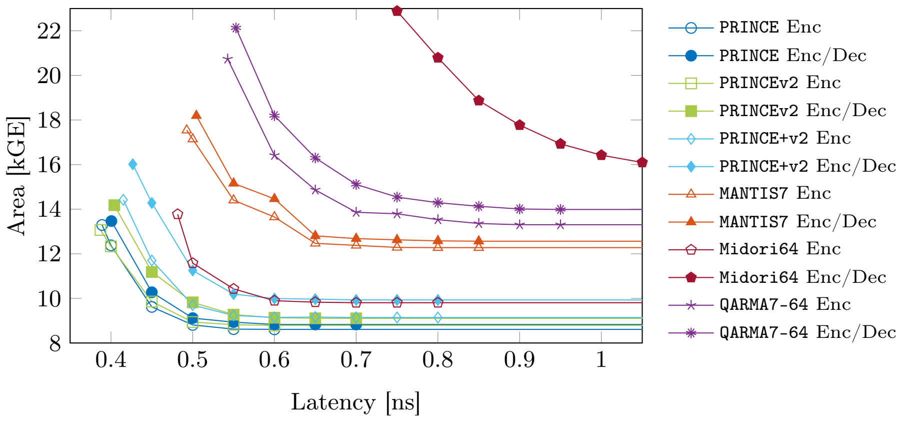


Fig. 6. Comparison of unrolled block ciphers in NanGate 15 nm Open Cell Library.

our base-implementation used for the construction of PRINCEv2 and PRINCE+v2 (and partially for $\mathtt{MANTIS}_7$) is well optimized.

Finally, we compare the energy consumption of the 6 ciphers. As detailed before, open-source libraries are not suitable for power and energy estimation. Thus, we have performed the energy comparison in the commercial 40 nm Low Power CMOS technology. This particular technology proved to be the most energy efficient, as apparent from Tables 3 and 4. The results have been estimated at 50 MHz and are depicted in Figure 7. Please note the y-axis limits on the bar graph. The differences between the circuits are not as large as they may appear at first sight. Yet, the results confirm once again that PRINCE and PRINCEv2 are the most cost-efficient unrolled circuits.

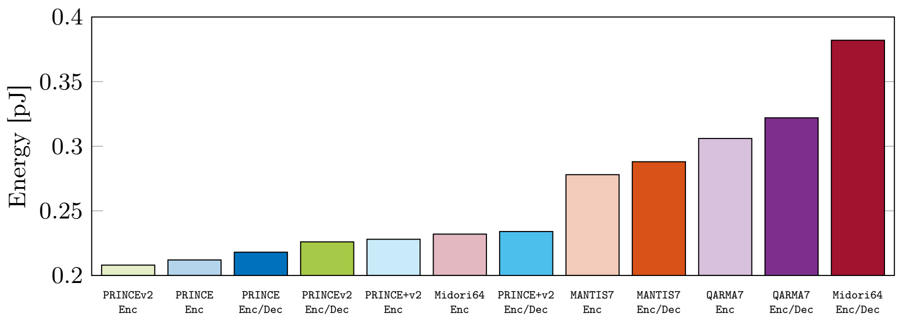


Fig. 7. Average energy consumption of unrolled block ciphers clocked at 50 MHz in a commercial 40 nm Low Power CMOS technology.

5 Security Analysis

We analyzed the security of `PRINCEv2` building on the previously published analysis of `PRINCE`. Most dedicated attacks on `PRINCEv2` are comparable to `PRINCE`, while `PRINCEv2` offers significantly better resistance to generic attacks. We show that several attacks successful against `PRINCE`, such as certain accelerated exhaustive search and meet-in-the-middle attacks, do not apply to `PRINCEv2`. Note that we do not consider analyses of variants with modified operations or related-key attacks, but we provide a discussion of the latter at the end of this section.

Since `PRINCEv2` is designed to provide a higher security level, we also need to consider attacks with higher complexity than for `PRINCE`. For several dedicated attack strategies, we find attacks that cover 1 or 2 more rounds with significantly higher time complexity T or data complexity D. This higher complexity is above the bound $D \cdot T < 2^{126}$ claimed for `PRINCE`, but below the generic bounds of $D < 2^{64}$, $T < 2^{128}$ for `PRINCEv2`, and thus relevant to judge the security margin of `PRINCEv2`. We note that the security claim for `PRINCEv2` limits the attacker to $D < 2^{47}$ and $T < 2^{112}$, while most of the results we propose for round-reduced `PRINCEv2` require more data than permitted by this bound.

Additionally, we provide several new results, including a linear attack, a 6-round integral distinguisher based on the division property, a more precise evaluation of boomerang attacks using recently published techniques, and a new 10-round Demirci-Selçuk meet-in-the-middle attack.

Table 7 provides an overview of the highlights of this section, including the best attacks on `PRINCEv2` and noteworthy new results. In summary, `PRINCEv2` is at least as secure as `PRINCE` against various dedicated attacks and provides better generic security.

Differential [ALL12,CFG⁺14a,CFG⁺14b,DP15a,DP15b,GR16a,GR16b]: The truncated differential used in [GR16a,GR16b] applies the subspace trail technique and attacks at most 6 rounds of `PRINCE`, which is the same for `PRINCEv2`.

Table 7. Overview of the main analysis results on round-reduced PRINCEv2, where 12 is the full number of rounds. Time complexity is given in computation equivalents, data complexity in known plaintexts (KP) or chosen plaintexts (CP). For most attacks in this table except meet-in-the-middle (†), the attacks on PRINCE apply to PRINCEv2 with similar complexity and vice-versa; however, the complexity of the attacks listed for PRINCEv2 is higher than permitted by the PRINCE security claim. For other results, refer to details in Section 5.

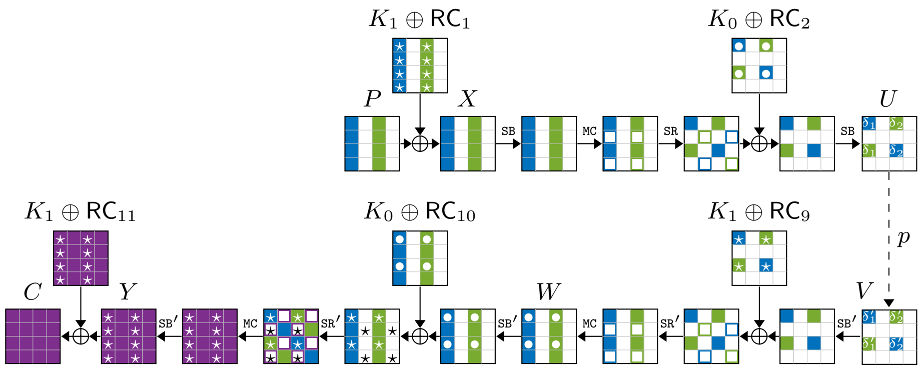
Attack	Target		Complexity		Reference
	Version	Rounds	Time	Data	
Differential	PRINCE	10	2^{61}	2^{58} CP	[CFG+14a]
	PRINCEv2	11	2^{92}	2^{59} CP	New
Impossible differential	PRINCE	7	2^{54}	2^{56} CP	[DZLY17]
	PRINCEv2	9	$e^{-\alpha} \cdot 2^{128}$	$\alpha \cdot 2^{65}$ CP	New
Integral	PRINCE	7	2^{57}	2^{60} CP	[Mor17]
	PRINCEv2	8	$2^{107.4}$	2^{36} CP	New
Meet-in-the-middle	PRINCE †	10	2^{122}	2 KP	[RR16b]
	PRINCEv2 †	10	2^{112}	2^{48} CP	New

The inside-out differential in [ALL12] took advantage of the key-less middle round to attack at most 6 rounds of PRINCE and is thus not applicable to PRINCEv2.

The most powerful differential attack against PRINCE was the one introduced in [CFG+14a,CFG+14b] that covers 10 rounds using $2^{57.94}$ chosen plaintexts, $2^{60.62}$ computations and $2^{61.52}$ blocks of memory. The distinguisher of this attack covers 6-round and it appends 2 rounds before and 2 rounds after which needs to guess 66 key bits. Using the same distinguisher and attack for PRINCEv2, we need to guess 64 key bits. The complexities of both attacks are roughly the same. The probability of the corresponding differentials are summarized in Table 8.

This attack can be extended by one round with the new key schedule at the cost of significantly higher time complexity, as illustrated in Figure 8.

1. Query N_s structures of 2^{32} chosen plaintexts P with columns P_1, P_3 fixed within each structure. This yields $N_s \cdot 2^{31} \cdot (2^{32} - 1) \approx N_s \cdot 2^{63}$ candidate pairs as in Figure 8.
2. For each of the $N_s \cdot 2^{63}$ candidate pairs (P, P'), we expect 1 candidate for the 96-bit key $(K_1, K_{0,0}, K_{0,2})$, which can be determined by a small number of table lookups:
   (a) We expect 1 key candidate for the key columns $K_{1,0}, K_{1,2}$ ($\star$) that satisfies the pattern through SB, MC in rounds 1 and 11. This costs one lookup in a precomputed table $(\Delta X_0, \Delta Y_0, X_0 \oplus Y_0) \to X_0$ per pair.
   (b) For any fixed difference ΔU, we also get 1 key candidate for the 4 nibbles of K_0 involved in round 2, which determines 4 nibbles of W in round 10 ($\bullet$).



$K_1 \oplus \mathsf{RC}_1$
$K_0 \oplus \mathsf{RC}_2$
P
X
SB
MC
SR
SB
U
p
$K_1 \oplus \mathsf{RC}_{11}$
$K_0 \oplus \mathsf{RC}_{10}$
$K_1 \oplus \mathsf{RC}_9$
C
Y
SB′
MC
SR′
SB′
W
MC
SR′
SB′
V
δ_1
δ_2
δ'_1
δ'_2

Fig. 8. Differential attack on 11-round `PRINCEv2` extending [CFG+14a] by one round.

(c) Due to the pattern for `MC` in round 10, there are only $2^8 \times 2^8$ possible differences ΔW. The key bits found so far determine 16 bits of this difference and thus on average fully determine ΔW.

(d) For any fixed difference ΔV, knowing $K_{1,0}, K_{1,2}$, we get on average 1 candidate for the value of the two active columns W_0, W_2. This determines the difference ΔZ and thus the key columns $K_{1,1}, K_{1,3}$ as well as the rest of $K_{0,0}, K_{0,2}$.

3. Rank the obtained $N_s \cdot 2^{63}$ candidates for the 96-bit key $(K_1, K_{0,0}, K_{0,2})$.

Using $N_s = 5/p/2^{31} = 2^{29}$ structures for the best differential $(\delta_0, \delta_1, \delta'_0, \delta'_1) = (\mathtt{1}, \mathtt{2}, \mathtt{1}, \mathtt{2})$ from Table 8, we expect about 5 right pairs, which should be easily sufficient for distinguishing. The remaining 32 key bits $(K_{0,1}, K_{0,3})$ can be recovered by brute-force search. The overall complexity is $N_s \cdot 2^{32} = 2^{61}$ chosen plaintexts and the time corresponding to $N_s \cdot 2^{63} = 2^{92}$ repetitions of a few table lookups and arithmetic operations, which can be roughly approximated by one encryption equivalent.

The attack can be slightly improved using multiple differentials from Table 8, but fewer structures. For example, we can use the 2^2 permutations of the best differential with the same p and decrease N_s by a factor of 2^2, obtaining an attack with the same expected number of valid pairs and key candidates, while the data complexity is reduced to 2^{59} and the time complexity is slightly lower than before.

Linear: Even though there is no published linear analysis for `PRINCE`, we find out that the activity patterns used in [CFG+14a] for differential analysis are also useful for the linear one. This is because of the `MC` operation that uses an involutive and self-transpose matrix, i.e. $M'^T = M'^{-1} = M'$. We compute the average square correlation of all 6-round linear hulls which follow the given activity patterns similarly as in [CFG+14a] for both `PRINCE` and `PRINCEv2`. These values are summarized in Table 8.

Table 8. Differentials and linear hulls fitting to the 6-round activity patterns given in [CFG$^+$14a] for both `PRINCE` and `PRINCEv2`.

differential probability (divided by $2^{-72} \times 2^3$)			
(δ_0, δ_1)	(δ'_0, δ'_1)	`PRINCE`	`PRINCEv2`
(1,2)	(1,2)	6144	2560
(1,2)	(1,8)	3328	1344
(1,2)	(1,a)	1664	672
(1,2)	(4,2)	1536	640
(1,2)	(4,8)	1664	928
(1,2)	(4,a)	832	336
(1,8)	(1,8)	2112	784
(1,8)	(1,a)	1056	392
(1,8)	(4,2)	832	336
(1,8)	(4,8)	1056	520
(1,8)	(4,a)	528	196
(1,a)	(1,a)	528	196
(1,a)	(4,2)	416	168
(1,a)	(4,8)	528	260
(1,a)	(4,a)	264	98
(4,2)	(4,2)	384	160
(4,2)	(4,8)	416	232
(4,2)	(4,a)	208	84
(4,8)	(4,8)	656	388
(4,8)	(4,a)	264	130
(4,a)	(4,a)	132	49

average square linear correlation (divided by $2^{-91} \times 2^3$)			
(δ_0, δ_1)	(δ'_0, δ'_1)	`PRINCE`	`PRINCEv2`
(4,2)	(4,2)	3563313280	2701826048
(4,2)	(4,8)	243931552	177559040
(4,2)	(4,a)	215632256	165965824
(4,2)	(5,2)	44716840	22956032
(4,2)	(5,8)	23525008	14792960
(4,2)	(5,a)	3662080	2491520
(4,8)	(4,8)	16864144	11669888
(4,8)	(4,a)	14706248	10906624
(4,8)	(5,2)	3338620	1510400
(4,8)	(5,8)	1723948	972992
(4,8)	(5,a)	256192	163616
(4,a)	(4,a)	13067272	10194944
(4,a)	(5,2)	2613530	1409536
(4,a)	(5,8)	1385768	908416
(4,a)	(5,a)	219776	153088
(5,2)	(5,2)	1221068	203976
(5,2)	(5,8)	698555	133008
(5,2)	(5,a)	54472	20960
(5,8)	(5,8)	466562	87600
(5,8)	(5,a)	27160	13544
(5,a)	(5,a)	4024	2312

One can use these linear hulls to analyze 10-round `PRINCE` by guessing 66 key bits and on `PRINCEv2` with 64 key bits guesses (similar to differential attack). Data complexity for both of these attacks are factor of 2^{57} known plaintexts.

Impossible Differential [DZLY17]: The best previously known impossible differential attack was discovered by Ding *et al.* [DZLY17], based on a 4-round distinguisher and extended to an attack up to 7 rounds with 2^{56} data, $2^{53.8}$ time and 2^{43} bytes of memory. At Eurocrypt'17, Sasaki and Todo proposed a new way to search for impossible differentials [ST17] based on MILP, leading to much more sophisticated distinguishers than previously known. We implemented this algorithm and were able to find new impossible distinguishers over 5 rounds which are given in Table 9. Note that there are two different configurations for our distinguishers: either $1 + 2 + 2$ which means one forward round, the two middles rounds and 2 backward rounds, or $2 + 2 + 1$, *i.e.*, two forward rounds, two middle rounds and one backward round.

Table 9. Impossible differential distinguishers for 5 rounds.

2 + 2 + 1 Rounds	1 + 2 + 2 Rounds
0010000000000000 $\not\rightarrow$ 0000000040000000	0400000000000000 $\not\rightarrow$ 0000000000004000
0000000000100000 $\not\rightarrow$ 0000000001000000	0010000000000000 $\not\rightarrow$ 0000000000000010
0000000000004000 $\not\rightarrow$ 0400000000000000	0000000040000000 $\not\rightarrow$ 0010000000000000
0000000000000010 $\not\rightarrow$ 0010000000000000	0000000001000000 $\not\rightarrow$ 0000000000100000

Due to the specific shape of these impossible differentials (only one active bit in the input and output), we can take any one of them and use it to mount an attack up to 9 rounds. Using [BNPS14], we were able to estimate that the resulting attack would need $\alpha \cdot 2^{65}$ data and memory, and $2^{128} \cdot e^{-\alpha}$ time, where α is a parameter allowing for a trade-off between data/memory and time complexities (the higher is α, the higher is the data/memory complexity and the lower is the time complexity).

Integral and Higher-Order Differential [JNP+13,Mor17,PN15,RR16c]: The longest known distinguisher of these types is a higher-order differential that is introduced in [Mor17]. This distinguisher includes 5 nonlinear layers and needs a data set of size 2^{32}. For key recovery, it is possible to append at most 3 rounds to the end of distinguisher and attack 8 round `PRINCEv2` by guessing 80 key bits. The complexity of this attack is 2^{112} computations (equivalent to $2^{107.4}$ 8-round `PRINCEv2` encryption), 2^{36} chosen plaintexts and 2^{36} blocks of memory.

A more recent technique to build integral distinguisher is to use the so-called *division property* introduced by Todo at Eurocrypt'15 [Tod15]. This technique was later refined into *bit-based division property* at FSE'16 by Todo and Morii [TM16] and some work was done to efficiently search for division property using *e.g.* Mixed Integer Linear Programming (MILP) [XZBL16,ZR19]. We implemented this algorithm to search for division property based distinguishers and we ended up finding such a distinguisher over 6 rounds. This distinguisher requires 2^{62} chosen plaintexts and due to this high data complexity, we do not expect it to be used to mount an attack over more than 8 rounds while also having better complexities than the above-mentioned attack.

Boomerang [PDN15]: The boomerang attack is applied to `PRINCE` in [PDN15], but there are some flaws on the estimation of the probability, e.g., the effect of the boomerang switching [BK09] is not taken in consideration. The so-called sandwich attack [DKS10,DKS14] is an experimental approach to estimate more rigorously this probability. We estimated the probability for a boomerang distinguisher with 4-round plus the middle layer. The probability of this 6-round distinguisher is about 2^{-34}, but the 7-round distinguisher is clearly worse than the classical differential attack because it involves 9 additional active S-boxes.

Accelerated Exhaustive Search [JNP+13,PDN15,RR16a,RR16b]: These attacks on `PRINCE` either used the α-reflection and FX-construction property or the key-less middle rounds of the cipher to accelerate the exhaustive search. For PRINCEv2, these properties do not hold anymore and the only possible attack of this type is the one used in [RR16b]. Using the technique of [RR16b] and by starting from the middle of the cipher, attacking 4 round or more requires to guess all the key bits. By starting from the plaintext/ciphertext side, attacking 6 rounds or more requires to guess all the key bits.

Meet-in-the-Middle [CNPV13a,CNPV13b,DP15a,DP15b,LJW13,RR16b]: Meet-in-the-Middle attacks used in [LJW13,RR16b] took advantage of key-less middle rounds and use super-sboxes in the middle of the cipher to attack at most 10 rounds. These attacks do not work on PRINCEv2 as effective as on PRINCE.

The sieve-in-the-middle attack, introduced in [CNPV13a,CNPV13b], is applicable to 8 rounds of PRINCE which includes 6 rounds for the sieve-in-the-middle and 2 rounds for the biclique part. Applying it to PRINCEv2, the sieve-in-the-middle part will be more complicated. The super-sbox used there will be key-dependent, which increases the time and memory complexity.

The meet-in-the-middle attack used in [DP15a,DP15b] reaches 10 rounds of PRINCE. Applying the tool given in [Der19] by Patrick Derbez which uses the same technique, we find out that it is possible to attack at most 6 rounds of PRINCEv2 with the complexity of either 2^{96} computations and 2^{26} memory blocks or 2^{112} computations and 2^{6} memory blocks.

We also analyzed the security of PRINCEv2 against Demirci-Selçuk meet-in-the-middle attacks using the same tool by Derbez. This attack can reach at most 10 rounds using 2^{48} chosen plaintexts, 2^{112} computations and 2^{70} memory blocks.

Time-Data-Memory Trade-Offs [Din15,JNP+13]: Excluding trivial Diffie-Hellman time-data-memory trade-offs, all of these attacks used FX-construction property of the PRINCE and do not work on the PRINCEv2.

Biclique [ALL12,YPO15]: These attacks could accelerate an exhaustive search maximally by a factor of 2, exploiting the FX-construction in PRINCE. Since PRINCEv2 is not an FX-construction anymore and this attack does not improve the exhaustive search generally, we expect this attack to be not applicable.

Collisions [FJM14]: The FX-construction of PRINCE allows a collision-based attack, using 2^{32} data, 2^{96} off-line and 2^{32} on-line computations, to recover the key. But again, it does not apply to PRINCEv2.

Remarks about Related-Key Attacks: We emphasize that we never claim any security under related-key attacks, but it is also important to understand the impact on PRINCEv2 when attackers can use related-key attacks.

First of all, when both rotational and XOR-difference relations are allowed, the trivial related-key distinguishing attack is possible by exploiting the convertible property from encryption to decryption. Even if the relationship is restricted to XOR-difference, attackers can still attack PRINCEv2 by using related-key boomerang attacks. The related-key boomerang attack is applied to PRINCE without whitening keys in [JNP+13]. Inducing differences with the key allows attackers to construct iterative related-key differential characteristics whose number of active S-boxes is only one in each round. This iterative property is lost in the middle round R', but attackers can overcome R' by using related-key boomerang attack, where two iterative related-key differential characteristics are connected. The new key schedule for `PRINCEv2` is not designed to avoid this related-key boomerang attack, and there are related-key boomerang characteristics with 12 active S-boxes. Similarly to the single-key boomerang attack, evaluating the probability in detail requires to analyze the effect of the boomerang switching. However, we can estimate the probability is roughly $2^{-12\times2\times2} = 2^{-48}$ from the number of active S-boxes, and it implies that `PRINCEv2` is not secure against the related-key attack.

Again, we never claim any security under related-key attacks, and we believe that a related-key attack never happens in the environment that `PRINCEv2` is demanded.

6 Conclusion

The need for a secure and efficient low-latency block cipher which also has low-power and low-energy requirements is ever increasing with the widespread of multiple technologies using microcontrollers. While `PRINCE` family of block ciphers were specifically designed to tackle this problem, the recent lightweight crypto competition for AEAD from the NIST set a specific security level that `PRINCE` cannot reach. As a low-latency cipher would probably be deployed in a larger environment using such an AEAD primitive, it makes sense to want this low-latency cipher to reach the same security level. We show how to modify `PRINCE` to reach the required security level set by the NIST while minimizing the induced overhead, especially in a situation where `PRINCE` is already deployed.

We solve this problem by showing that a carefully built key-schedule is sufficient to provide the required security goal while keeping (almost) all of the remaining design untouched and propose `PRINCEv2` family of block ciphers. As proven by our various experiments, `PRINCEv2` only has a very small overhead compared to `PRINCE`, while still reaching the required higher security level. Moreover, the fact that the `PRINCE` and `PRINCEv2` designs are very similar allows one to implement both `PRINCE` and `PRINCEv2` in the same environment (e.g., for backward compatibility) with a very small overhead.

Finally, the similarities between `PRINCE` and `PRINCEv2` allow us to reuse a majority of the security analysis done by the community over the last 8 years since `PRINCE`'s publication. By doing so and carefully analyzing how the modifications made influenced the previously known attacks on `PRINCE`, as well as providing new cryptanalysis insights for both versions, we showed that `PRINCEv2` meets its security requirements.

We thus believe that `PRINCEv2` is a major improvement over `PRINCE` and we expect it to be widely adopted in the near future. Moreover, our work shows that one can improve the security level of some lightweight primitives with minimal downsides. An open question is thus to see if similar improvements could be made for other microcontroller-targeted ciphers such as `Midori`, `MANTIS` and `QARMA`, which could lead to interesting future work.

We made the reference implementation publicly available on GitHub in:

`https://github.com/rub-hgi/princev2`

Acknowledgments

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A Code

SageMath code to generate the round constants:

```
a = RealField(prec=2000)(pi)-3
for i in range(1, 9):
b = (floor(a*2^(64*i)) + 2^64) % 2^64
print("0x%016x" % (b))
```

The output is:

```
0 0x243f6a8885a308d3
1 0x13198a2e03707344
2 0xa4093822299f31d0
3 0x082efa98ec4e6c89
4 0x452821e638d01377
5 0xbe5466cf34e90c6c
6 0xc0ac29b7c97c50dd
7 0x3f84d5b5b5470917
```

The 0th constant is not used in `PRINCE`, so we skip it, too. The second last constant (line 6) is α and thus we use the last one (line 7) as β.

B Test Vectors

Plaintext	k_0	k_1	Ciphertext
0000000000000000	0000000000000000	0000000000000000	0125fc7359441690
ffffffffffffffff	0000000000000000	0000000000000000	832bd46f108e7857
0000000000000000	ffffffffffffffff	0000000000000000	ee873b2ec447944d
0000000000000000	0000000000000000	ffffffffffffffff	0ac6f9cd6e6f275d
0123456789abcdef	0123456789abcdef	fedcba9876543210	603cd95fa72a8704

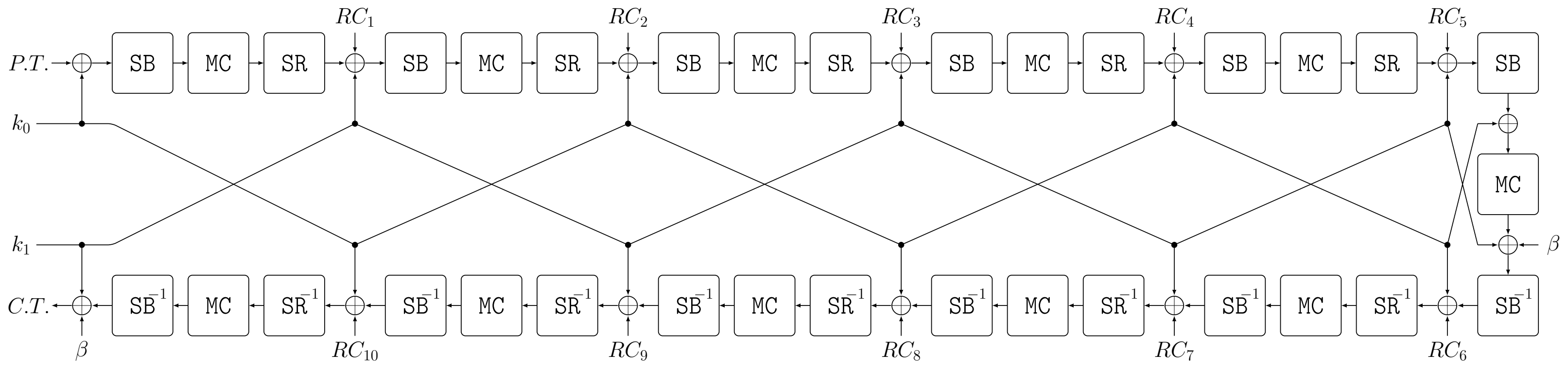

Fig. 9. PRINCEv2 structure for encryption.

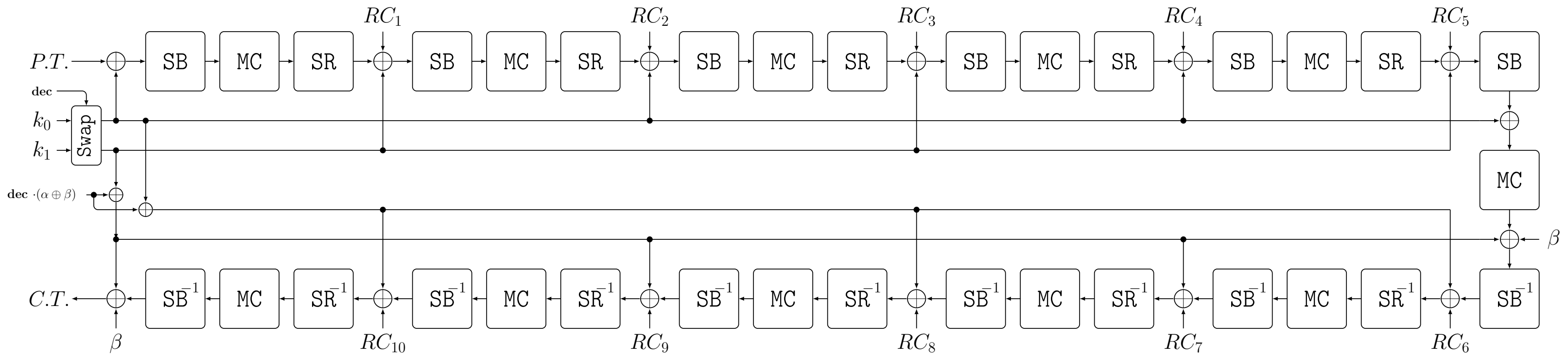

Fig. 10. PRINCEv2 structure for encryption and decryption.