π—Cipher v2

Designers: Danilo Gligoroski\(^2\) and Hristina Mihajloska\(^3\) and Simona Samardjiska\(^3\) and Håkon Jacobsen\(^2\) and Mohamed El-Hadedy\(^2\) and Rune Erlend Jensen\(^4\)

Submitter: Hristina Mihajloska
hristina.mihajloska@finki.ukim.mk

28.11.2014

1Since, the name of the cipher contains the Greek letter π, in the software implementations we will use the name Picipher. More precisely in this document we propose the following six variants of the cipher: Pi16Cipher096v2, Pi16Cipher128v2, Pi32Cipher128v2, Pi32Cipher256v2, Pi64Cipher128v2, Pi64Cipher256v2

\(^2\)ITEM, Norwegian University of Science and Technology, Trondheim, Norway
\(^3\)FCSE, "Ss Cyril and Methodius" University, Skopje, Republic of Macedonia
\(^4\)IDI, Norwegian University of Science and Technology, Trondheim, Norway
Chapter 1

Specification

1.1 Parameters, variables and constants

The following parameters and variables are used in the specification of \( \pi \)-Cipher:

- \( \pi \omega \)-Cipher: AEAD cipher defined with \( \omega \)-bit words and \( n \)-bit security.
- \( \omega = 16, 32, 64 \): Size of binary words in bits that are used in \( \pi \)-Cipher.
- \( \pi \) function: Main permutation function of the cipher.
- \( M \): Message or plaintext.
- \( mlen \): Length of a message less than \( 2^{64} - 1 \) bytes.
- \( m \): Number of message blocks.
- \( K \): Secret key.
- \( klen \): Length of a key \( K \) in bytes. It can be 12 bytes (96 bits), 16 bytes (128 bits) or 32 bytes (256 bits).
- \( AD \): Associated data. This data cannot be encrypted or decrypted.
- \( adlen \): Length of an associated data less than \( 2^{64} - 1 \) bytes.
- \( a \): Number of associated data blocks.

Thus, \( AD = AD_1 || AD_2 || \ldots || AD_a \).
1.1 Parameters, variables and constants

**IS**  
Internal state, bijectively transformed by the $\pi$ function. Throughout this document when IS is used as a common internal state for many parallel computations, we will use the abbreviation CIS (Common Internal State).

**$I_i$**  
Chunk from the internal state IS. It is a 4-tuple of $\omega$-bit words. $I_i = (IS_{i1}, IS_{i2}, IS_{i3}, IS_{i4})$.

**$N$**  
The internal state IS is divided into $N$ chunks of length $4 \times \omega$. $N$ is even number and $N \geq 4$. Thus, $IS = (I_1, I_2, \ldots, I_N)$.

**$b$**  
Size of IS in bits. It is constrained by the following relation: $b = N \times 4 \times \omega$.

**bitrate**  
Rate of the IS from the sponge construction paradigm point of view. $IS_{bitrate} = I_1 \| I_3 \| \ldots \| I_{N-1}$.

**capacity**  
Capacity of the IS from the sponge construction paradigm point of view. $IS_{capacity} = I_2 \| I_4 \| \ldots \| I_N$.

| || || ||  
| Operator of interleaved concatenation in order to correctly denote a concatenation of $IS_{bitrate}$ and $IS_{capacity}$ that restores IS i.e., $IS = IS_{bitrate} || IS_{capacity}$.

**$PMN$**  
Public message number. The size $|PMN|$ in bits is constrained by the following relation: $8 \times klen + |PMN| + 8 \leq b$.

**$SMN$**  
Secret message number. The size $|SMN|$ in bits is constrained by the following relations: $|SMN| = 0$ or $|SMN| = bitrate$.

**NONCE**  
NONCE = $(PMN, SMN)$.

**$C$**  
Ciphertext.

**clen**  
Length of the ciphertext in bytes, where $clen = mlen + |SMN| + tlen$ (here $|SMN|$ is in bytes).
1.2 General design properties

Authentication tag for the message, NONCE and associated data.

Length of the authentication tag in bytes. It is constrained by the following relation: \( tlen = \frac{\text{bitrate}}{8} \).

Tweakable parameter that represents the number of rounds in \( \pi \) function.

64-bit counter used in the cipher. It is initialized from the first 64 bits of the \( IS_{capacity} \).

Operation of componentwise addition of two \( d \)-dimensional vectors of \( \omega \)-bit words in \( (Z_{2^\omega})^d \).

\( \pi \)-Cipher is designed for different word sizes and different security levels. The recommended variants are presented in Table 1.1.

Table 1.1: Basic characteristics of all variants of the \( \pi \)-Cipher

<table>
<thead>
<tr>
<th>Word size ( \omega )</th>
<th>klen (in bits)</th>
<th>PMN (in bits)</th>
<th>SMN (in bits)</th>
<th>b (in bits)</th>
<th>N</th>
<th>bitrate (in bits)</th>
<th>Tag t (in bits)</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi16 )-Cipher096</td>
<td>16</td>
<td>96</td>
<td>32</td>
<td>0 or 128</td>
<td>256</td>
<td>4</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>( \pi16 )-Cipher128</td>
<td>16</td>
<td>128</td>
<td>32</td>
<td>0 or 128</td>
<td>256</td>
<td>4</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>( \pi32 )-Cipher128</td>
<td>32</td>
<td>128</td>
<td>128</td>
<td>0 or 256</td>
<td>512</td>
<td>4</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td>( \pi32 )-Cipher256</td>
<td>32</td>
<td>256</td>
<td>128</td>
<td>0 or 256</td>
<td>512</td>
<td>4</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td>( \pi64 )-Cipher128</td>
<td>64</td>
<td>128</td>
<td>128</td>
<td>0 or 512</td>
<td>1024</td>
<td>4</td>
<td>512</td>
<td>512</td>
</tr>
<tr>
<td>( \pi64 )-Cipher256</td>
<td>64</td>
<td>256</td>
<td>128</td>
<td>0 or 512</td>
<td>1024</td>
<td>4</td>
<td>512</td>
<td>512</td>
</tr>
</tbody>
</table>

1.2 General design properties

\( \pi \)-Cipher is parallel, incremental, nonce based authenticated encryption cipher with associated data that offers some level of tag second-preimage resistance. It involves several solid cryptographic concepts such as:
1. The design belongs to the category of Encrypt-then-MAC authenticated ciphers.

2. Its parallel and incremental design is similar to the design of the counter based XOR MAC scheme of [1], but in order to achieve the second-preimage resistance for the MAC tags, instead of XOR operations for the intermediate tag components we use componentwise additions in $(\mathbb{Z}_2^\omega)^d$.

3. In [3, Sec. 3.3] the authors mention that it is possible to construct an authenticated encryption using two pass sponge construction [2] that is proven to be secure as long as the underlying sponge permutation has no structural distinguishers. In the same paper [3] the duplex sponge construction is introduced. Although these constructions have the property to be tag second-preimage resistant, neither of them is incremental. An incremental and parallel two pass scheme is proposed in [7]. However, the design goal for that scheme was not to be tag second-preimage resistant. Combining all these ideas, in our design we use a two pass counter based sponge component that we call triplex component. The used $\pi$ permutation is based on ARX (Addition, Rotation and XOR) operations.

### 1.2.1 Authenticated encryption

The encryption/authentication procedure of $\pi$-Cipher accepts key $K$ with fixed-length of $klen$ bytes, message $M$ with $mlen$ bytes and associated data $AD$ with $adlen$ bytes. The cipher uses a fixed-length public message number $PMN$ and secret message number $SMN$. The output of the encryption/authentication procedure is a ciphertext $C$ with $clen$ bytes and a tag $T$ with fixed-length of $tlen$ bytes. The length $clen$ of the ciphertext $C$ is a sum of the byte length of the message, the authentication tag and the encrypted secret message number. The decryption/verification procedure accepts key $K$, associated data $AD$, ciphertext $C$, public message number $PMN$, secret message number $SMN$ and tag $T$, and returns the decrypted message $M$ if the tag has been verified or $\perp$ otherwise.

The main building element in the operations of encryption/authentication and decryption/verification is our new construction related to the duplex sponge, called triplex component. It uses the permutation function $\pi$ twice, it injects a counter into the internal state and digests an input string. The triplex component always outputs a tag. Optionally after the first call of the permutation function it can output a string (that can be a ciphertext block or a message block). The general scheme of the triplex component
1.2 General design properties

Figure 1.1: A general scheme of the triplex component

Because of the differences in the encryption/authentication and decryption/verification procedures, there are two different variants of the triplex component. We call them e-triplex (for the phase of encryption) and d-triplex (for the phase of decryption). The only difference in these two components is how the input string is treated after the first call of the permutation function. In the first one, the input string (plaintext) is XORed with the current internal state and the result proceeds to the second invocation of the permutation function $\pi$. In the d-triplex component, the input string (ciphertext) is directly injected as a part of the internal state before the second invocation of the permutation function $\pi$. The graphical representation of the e-triplex and d-triplex components is given in Figure 1.2.

Figure 1.2: Triplex component

is presented in Figure [1.1]

The encryption/authentication operation of $\pi$-Cipher can be described in four phases:

1. Initialization. In this phase we append a single "1" (i.e., 0x01 in hexadecimal
byte representation) and the smallest number of 0’s (i.e., 0x00 in hexadecimal byte representation) to the concatenated value of the key and the public message number. The length of the result should be less than or equal to the length of the internal state of the permutation function $\pi$. In other words the internal state is initialized with $K||PMN||10^*$. Then the internal state is updated by applying the permutation function $\pi$. Because, $\pi$-Cipher works in parallel mode, it has an initial value for the state for all of the parallel parts. We call it Common Internal State (CIS). The CIS is initialized as:

$$CIS \leftarrow \pi(K||PMN||10^*).$$

The next part of this phase is initializing the counter $ctr$.

Since $CIS = CIS_{\text{bitrate}}||CIS_{\text{capacity}}$ we initialize the $ctr$ as the first 64 bits (little endian representation) of the $CIS_{\text{capacity}}$.

The graphical representation of the Initialization phase is given in Figure 1.3.

2. **Processing the associated data.**

The associated data $AD = AD_1||\ldots||AD_i||\ldots||AD_a$ is processed block by block in parallel using e-triplex components. The padding rule for the associated data $AD$ is the following:

$$AD = AD_1||AD_2||\ldots||AD_a||10^*$$

where 1 represents the byte 0x01, and 0 represents the byte 0x00. Note that if the associated data $AD$ has length that is a multiple of the bitrate, then the number of processed blocks of $AD$ is increased by one, and thus $a \leftarrow a + 1$.

To every block $AD_i$ we associate a unique counter calculated as a sum of the initial counter $ctr$ and the ordinal number of the processed block $i$. The input to every e-triplex component is $CIS$, $ctr + i$ and $AD_i$, and the output is a block tag $t'_i$.

The tag $T'$ for the associated data is computed as a component-wise addition $\oplus_d$ of $a$ vectors $t'_i \in (\mathbb{Z}_{2^\omega})^d$ of dimension $d$, where $d$ is the number of $\omega$-bit words in the bitrate. In other words,

$$T' = \bigoplus_{i=1}^{a} t'_i = t'_1 \oplus_d t'_2 \oplus_d \ldots \oplus_d t'_a$$
where \( t'_i = (t'_{i1}, t'_{i2}, \ldots, t'_{id}) \) is a \( d \)-dimensional vector of \( \omega \)-bit words.

The final part of this phase is to update the value of the Common Internal State \( CIS \). Updating the \( CIS \) is done by xoring it with the tag \( T' \) and applying the \( \pi \) permutation function i.e. by the following expression:

\[
CIS \leftarrow \pi(CIS_{\text{bitrate}} \oplus T' || | CIS_{\text{capacity}})
\]

This step is described graphically in Figure 1.4.

3. **Processing the secret message number.** This phase is omitted if the length of the secret message number \( SMN \) is 0 (it is the empty string). If \( SMN \) is not the empty string, then the first step in this phase is a call to the e-triplex component. The input is the following triplet: \( (CIS, ctr + a + 1, SMN) \), and the output is the following pair: \( (C_0, t_0) \). The second step of this phase is updating the \( CIS \) (for free) which becomes the value of the current internal state after the processing of \( SMN \). Formally, the updating can be described by the following two expressions:

\[
IS \leftarrow \pi(CIS_{\text{bitrate}} \oplus (ctr + a + 1) || | CIS_{\text{capacity}}),
\]

\[
CIS \leftarrow \pi(IS_{\text{bitrate}} \oplus SMN || | IS_{\text{capacity}})
\]

The tag produced from this phase is

\[
T'' = T' \boxplus d t_0.
\]
1.2 General design properties

Figure 1.4: Processing the associated data $AD$ with $a$ blocks in parallel
This phase is described graphically in Figure 1.5.

4. **Processing the message.** The message $M = M_1 || \ldots || M_j || \ldots || M_m$ is processed block by block in parallel by e–triplex components. The padding rule for the message $M$ is the following:

$$M = M_1 || M_2 || \ldots || M_m || 10^*$$

where 1 represents the byte 0x01, and 0 represents the byte 0x00. Note that if the message $M$ has length that is a multiple of the bitrate, then the number of processed blocks of $M$ is increased by one, and thus $m \leftarrow m + 1$.

To every block $M_j$ we associate a unique block counter. It can be calculated as:

$$ctr \leftarrow \begin{cases} 
ctr + a + j & \text{if } |SMN| = 0, \\
ctr + a + 1 + j & \text{if } |SMN| = \text{bitrate},
\end{cases}$$

where $j$ is the ordinal number of the processed block in the message, and $0 < j \leq m$.

The input to every e–triplex component is the $CIS$, the block $ctr$ and $M_j$, and the output is a pair $(C_j, t_j)$. By definition we put that the length of the final ciphertext block $C_m$ is the same as the length of the un-padded last plaintext block $M_m$ i.e., $|C_m| = |M_m|$. 

---

**Figure 1.5:** Processing the secret message number $SMN$
1.3 The $\pi$-function

The final tag $T$ is obtained as a $\boxplus_d$ sum of all block tags $t_j$ and the previously obtained tag $T^n$.

$$T = T^n \boxplus_d t_1 \boxplus_d \ldots \boxplus_d t_j \boxplus_d \ldots \boxplus_d t_m.$$ 

where $t_j = (t_{j1}, t_{j2}, \ldots, t_{jd})$ is a $d$-dimensional vector of $\omega$-bit words.

This phase is described graphically in Figure 1.6.

The output of the encryption/authentication procedure is the ciphertext

$$C = C_0 || C_1 || \ldots || C_m || T.$$ 

1.2.2 Decryption and verification

The decryption/verification procedure is defined correspondingly. There are four phases and the only difference is in the last two (so the Initialization phase and Processing the associated data phase are completely the same as in the encryption/authentication procedure).

The decryption of the $SMN$ is performed in the phase of Processing the secret message number. Thus, instead of using an $e$-triple component, we use a $d$-triple component. The input parameters are: $CIS$, incremented counter $ctr + a + 1$ and the ciphertext block $C_0$. The output is a pair $(SMN, t_0)$. The tag is processed in the same way as in the encryption/authentication procedure.

For the decryption of the rest of the ciphertext we continue to use a $d$-triple component (instead of $e$-triple). The output is now a decrypted message block and a tag value.

At the end, the supplied tag value $T$ is compared to the one computed by the algorithm. Only if the tag is correct, the decrypted message is returned.

1.3 The $\pi$-function

The core part of every sponge construction is the permutation function, and the whole security of the primitive relies on it. The design goal for our sponge construction was to obtain a strong permutation, which for different values of the parameter $\omega$ (the bit size of the words) provides different features, i.e. to be very efficient when $\omega = 64$ and lightweight when $\omega = 16$. 
Figure 1.6: Processing the message $M$ with $m$ blocks in parallel
### 1.3 The $\pi$-function

$\pi$-Cipher has ARX based permutation function which we denote as $\pi$ function. It uses similar operations as the operations used in the hash function Edon-R [5] but instead of using 8-tuples here we use 4-tuples. The permutation operates on a $b$ bits state and updates the internal state through a sequence of $R$ successive transformations - rounds. The state $IS$ can be represented as a list of $N$ 4-tuples, each of length $\omega$-bits, where $b = N \times 4 \times \omega$, i.e.,

$$ IS = \{(IS_{11}, IS_{12}, IS_{13}, IS_{14}), (IS_{21}, IS_{22}, IS_{23}, IS_{24}), \ldots, (IS_{N1}, IS_{N2}, IS_{N3}, IS_{N4})\}.$$

(1.1)

The general permutation function $\pi$ consists of three main transformations $\mu, \nu, \sigma : \mathbb{Z}_{2^\omega}^4 \to \mathbb{Z}_{2^\omega}^4$, where $\mathbb{Z}_{2^\omega}$ is the set of all integers between 0 and $2^\omega - 1$. These transformations do the work of diffusion and nonlinear mixing of the input.

The following operations are applied:

![Graphical representation of the ARX operation](image-url)
1.3 The $\pi$-function

Table 1.2: The rotation vectors used in $\mu$ and $\nu$.

<table>
<thead>
<tr>
<th>$\omega$</th>
<th>$r_{1,\omega}$</th>
<th>$r_{2,\omega}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>(1, 4, 9, 11)</td>
<td>(2, 5, 7, 13)</td>
</tr>
<tr>
<td>32</td>
<td>(5, 11, 17, 23)</td>
<td>(3, 10, 19, 29)</td>
</tr>
<tr>
<td>64</td>
<td>(7, 19, 31, 53)</td>
<td>(11, 23, 37, 59)</td>
</tr>
</tbody>
</table>

- Addition $+$ modulo $2^\omega$;
- Rotate left (circular left shift) operation, $ROTL^r(X)$, where $X$ is a $\omega$-bit word and $r$ is an integer with $0 \leq r < \omega$;
- Bitwise XOR operation $\oplus$ on $\omega$-bit words.

Let $X = (X_0, X_1, X_2, X_3)$, $Y = (Y_0, Y_1, Y_2, Y_3)$ and $Z = (Z_0, Z_1, Z_2, Z_3)$ be three 4-tuples of $\omega$-bit words.

Further, let us denote by $*$ the following operation:

$$Z = X * Y \equiv \sigma(\mu(X) \boxplus_4 \nu(Y))$$  \hspace{1cm} (1.2)$$

where $\boxplus_4$ is the component-wise addition of two 4-dimensional vectors in $(\mathbb{Z}_2^\omega)^4$.

An algorithmic definition of the $*$ operation over two 4-dimensional vectors $X$ and $Y$ for different word sizes is given in Table 1.9, Table 1.10 and Table 1.11.

Also a graphical representation of the $*$ operation is given in Figure 1.7.

The following is a formalization of the $*$ operation (adopted from [5]).

The left rotation of a $\omega$-bit word $X$ by $r$ positions denoted by $ROTL^r(X)$, can be expressed as a linear matrix–vector multiplication over the ring $(\mathbb{Z}_2^\omega)^4$ i.e. $ROTL^r(X) = E^r \cdot X$ where $E^r \in \mathbb{Z}_2^{\omega \times \omega}$ is a matrix obtained from the identity matrix by rotating its columns by $r$ positions in the direction top to bottom. Further on, if we have a vector $X \in (\mathbb{Z}_2^\omega)^4$ represented as $X = (X_0, X_1, X_2, X_3)$ and we want to rotate all $X_i$ by $r_i$ ($0 \leq i < 4$) positions to the left, then we denote the operation by $ROTL^r(X)$, where $r = (r_0, \ldots, r_3) \in \{0, 1, \ldots, \omega - 1\}^4$ is a rotation vector. The operation $ROTL^r(X)$ can also be represented as a linear matrix–vector multiplication over the ring $(\mathbb{Z}_2^\omega)^4$ i.e.
Table 1.3: The matrices $\hat{A}_1$, $A_2$, $\hat{A}_3$ and $A_4$.

<table>
<thead>
<tr>
<th>$\hat{A}_1$</th>
<th>$A_2$</th>
<th>$\hat{A}_3$</th>
<th>$A_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(const_{1,\mu\omega})$ (1 1 1 0)</td>
<td>(1 1 1 0)</td>
<td>(1 0 1 1)</td>
<td>(1 1 1 1)</td>
</tr>
<tr>
<td>$(const_{2,\mu\omega})$ (1 1 1 1)</td>
<td>(1 1 1 0)</td>
<td>(1 1 0 1)</td>
<td>(1 0 1 1)</td>
</tr>
<tr>
<td>$(const_{3,\mu\omega})$ (1 0 1 1)</td>
<td>(0 1 1 1)</td>
<td>(1 1 0 1)</td>
<td>(1 1 0 1)</td>
</tr>
<tr>
<td>$(const_{4,\mu\omega})$ (0 1 1 1)</td>
<td>(1 0 1 1)</td>
<td>(0 1 1 1)</td>
<td>(1 1 1 0)</td>
</tr>
</tbody>
</table>

$ROT_{L^r}(X) = D^r \cdot X$ where $D^r \in \mathbb{Z}_2^4 \times \mathbb{Z}_2^4$,

$$D^r = \begin{pmatrix} E^{r_0} & 0 & 0 & 0 \\ 0 & E^{r_1} & 0 & 0 \\ 0 & 0 & E^{r_2} & 0 \\ 0 & 0 & 0 & E^{r_3} \end{pmatrix},$$

and the submatrices $E^{r_i} \in \mathbb{Z}_2^4 \times \mathbb{Z}_2^4$, $0 \leq r_i < 4$ are obtained from the identity matrix by rotating its columns by $r_i$ positions in the direction top to bottom, and the submatrices $0 \in \mathbb{Z}_2^4 \times \mathbb{Z}_2^4$ are the zero matrices.

Furthermore, we use the following notations:

- $\hat{A}_1, \hat{A}_3 : \mathbb{Z}_2^4 \rightarrow \mathbb{Z}_2^4$ are two bijective transformations in $\mathbb{Z}_2^4$ over the ring $(\mathbb{Z}_2^\omega, +, \cdot)$ where $\omega = 8, 16, 32, 64$. The mappings $\hat{A}_i$, $i = 1, 3$ can be described as:

$$\hat{A}_i(X) = C_i + A_i \cdot X,$$

where $C_i \in \mathbb{Z}_2^4$, $i = 1, 2$ are two constant vectors and $A_1$ and $A_3$ are two $4 \times 4$ invertible matrices over the ring $(\mathbb{Z}_2^\omega, +, \cdot)$. Also these matrices are MDS (maximum distance separable) matrices which redound to have maximal diffusion of the bits. All elements in these two matrices are either 0 or 1, since we want to avoid the operations of multiplication (as more costly microprocessor operations) in the ring $(\mathbb{Z}_2^\omega, +, \cdot)$, and stay only with operations of addition.

- $A_2, A_4 : \mathbb{Z}_2^4 \rightarrow \mathbb{Z}_2^4$ are two linear bijective transformations that are described by two invertible matrices (we use the same notation: $A_2, A_4$) of order $q \times q$ over the ring $(\mathbb{Z}_2, +, \cdot)$ ($q = 4\omega$). Since we want to apply XOR operations on $\omega$–bit registers,
the matrices $A_2$ and $A_4$ will be of the form

$$
\begin{pmatrix}
B_{1,1} & B_{1,2} & B_{1,3} & B_{1,4} \\
B_{2,1} & B_{2,2} & B_{2,3} & B_{2,4} \\
B_{3,1} & B_{3,2} & B_{3,3} & B_{3,4} \\
B_{4,1} & B_{4,2} & B_{4,3} & B_{4,4}
\end{pmatrix},
$$

where $B_{i,j} \in \mathbb{Z}_2^\omega \times \mathbb{Z}_2^\omega$, $1 \leq i, j \leq 4$ are either the identity matrix or the zero matrix i.e. $B_{i,j} \in \{0, 1\}$.

Now we give the formal definitions for the permutations: $\sigma$, $\mu$ and $\nu$.

**Definition 1.** The transformation $\sigma : \mathbb{Z}_2^\omega \rightarrow \mathbb{Z}_2^\omega$ is defined as:

$$
\sigma(X_0, X_1, X_2, X_3) = (X_3, X_0, X_1, X_2)
$$

**Lemma 1.** The transformation $\sigma$ is a permutation.

**Definition 2.** The transformations $\mu : \mathbb{Z}_2^\omega \rightarrow \mathbb{Z}_2^\omega$ and $\nu : \mathbb{Z}_2^\omega \rightarrow \mathbb{Z}_2^\omega$ are defined as:

$$
\mu \equiv \hat{A}_1 \circ \text{ROTL}^{r_1,\omega} \circ A_2
$$

$$
\nu \equiv \hat{A}_3 \circ \text{ROTL}^{r_2,\omega} \circ A_4
$$

where the rotation vectors $r_{i,\omega}$, $i = 1, 2$, $\omega = 16, 32, 64$ are given in Table 1.2, and the matrices $\hat{A}_1$, $A_2$, $\hat{A}_3$ and $A_4$ are given in Table 1.3. In Table 1.3, the symbols $1, 0 \in \mathbb{Z}_2^\omega \times \mathbb{Z}_2^\omega$ denote the identity matrix and the zero matrix, and the constants const$^{-}_{i,\omega}$, $i = 1, 2$, $\omega = 16, 32, 64$ are given (in hexadecimal notation) in Table 1.4 and Table 1.5. The rationale for choosing these constants is given in Section 5.2.

**Table 1.4:** List of constants used in $\mu$ transformation.

<table>
<thead>
<tr>
<th>const$^{-}_{i,\omega}$</th>
<th>$\mu_{16}$</th>
<th>$\mu_{32}$</th>
<th>$\mu_{64}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0xF0E8</td>
<td>0x8D8B8778</td>
<td>0xF0E8E4E2E1D8D4D2</td>
</tr>
<tr>
<td>2</td>
<td>0xE4E2</td>
<td>0x7472716C</td>
<td>0xD1CCCAC9C6C5C3B8</td>
</tr>
<tr>
<td>3</td>
<td>0xE1D8</td>
<td>0x6A696665</td>
<td>0xB4B2B1ACAA9A6A5</td>
</tr>
<tr>
<td>4</td>
<td>0xD4D2</td>
<td>0x635C5A59</td>
<td>0xA39C9A999695938E</td>
</tr>
</tbody>
</table>
Lemma 2. The transformations $\mu$ and $\nu$ are permutations of $\mathbb{Z}_{2^\omega}, \omega = 16, 32, 64$.

Proof. The proof follows immediately from the fact that all transformations $\mathcal{A}_i$, $i = 1, 2, 3, 4$ and $\text{ROTL}^\omega_i$, $i = 1, 2$, $\omega = 16, 32, 64$ are expressed by invertible matrices over the rings $(\mathbb{Z}_{2^\omega}, +, \ldots), \omega = 16, 32, 64$ or over the ring $(\mathbb{Z}_2, +, \ldots)$. □

Theorem 1. The operation $*: (\mathbb{Z}_{2^\omega}^4)^2 \rightarrow \mathbb{Z}_{2^\omega}^4$ defined as:

$$X * Y = \sigma(\mu(X) \oplus_1 \nu(Y))$$

is a permutation. □

Let us recall equation (1.1) where the internal state is presented as $IS = (I_1, I_2, \ldots, I_N)$. One round of the $\pi$ function consists of two consecutive transformations $E_1$ and $E_2$ defined as follows.

Definition 3. The function $E_1 : (\mathbb{Z}_{2^\omega}^4)^{N+1} \rightarrow (\mathbb{Z}_{2^\omega}^4)^N$ used in the $\pi$ function is defined as:

$$E_1(C, I_1, \ldots, I_N) = (J_1, \ldots, J_N), \text{ where}$$

$$J_1 = C * I_1,$$

$$J_i = J_{i-1} * I_i, \text{ } i = 2, \ldots, N$$

where $C$ is a 4-tuple of $\omega$-bit constant values.

Definition 4. The function $E_2 : (\mathbb{Z}_{2^\omega}^4)^{N+1} \rightarrow (\mathbb{Z}_{2^\omega}^4)^N$ used in $\pi$ function is defined as:

$$E_2(C, I_1, \ldots, I_N) = (J_1, \ldots, J_N), \text{ where}$$

$$J_N = I_N * C,$$

$$J_{N-i} = I_{N-i} * J_{N-i+1}, \text{ } i = 1, \ldots, N - 1$$

### Table 1.5: List of constants used in $\nu$ transformation.

<table>
<thead>
<tr>
<th>consti,ω</th>
<th>$\nu_{16}$</th>
<th>$\nu_{32}$</th>
<th>$\nu_{64}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0xD1CC</td>
<td>0x5655534E</td>
<td>0x8D8B87787472716C</td>
</tr>
<tr>
<td>2</td>
<td>0xCA6C9</td>
<td>0x4D4B473C</td>
<td>0xA69665635C5A59</td>
</tr>
<tr>
<td>3</td>
<td>0xCA3C5</td>
<td>0xA393635</td>
<td>0x5655534E4D4B473C</td>
</tr>
<tr>
<td>4</td>
<td>0xCA3B8</td>
<td>0x332E2D2B</td>
<td>0xA393635332E2D2B</td>
</tr>
</tbody>
</table>
where $C$ is a 4-tuple of $\omega$-bit constant values.

Finally, one round of the $\pi$ function is defined as:

$$\pi(I_1, \ldots, I_N) = E_2(C_2, E_1(C_1, I_1, \ldots, I_N))$$ (1.5)

One round of the cipher is graphically described in Figure 1.8. In the figure, the diagonal arrows can be interpreted as $\ast$ operations between the source and destination, and the vertical or horizontal arrows as equality signs "\(^\ast\) = ".

![Figure 1.8: One round of $\pi$-Cipher](image)

The number of rounds $R$ is a tweakable parameter. We recommend $R = 4$. The complete formula for the $\pi$ function with $R = 4$ is the following:

$$\pi(I_1, \ldots, I_N) = E_2(C_8, E_1(C_7, E_2(C_6, E_1(C_5, E_2(C_4, E_1(C_3, E_2(C_2, E_1(C_1, I_1, \ldots, I_N))))))))$$

The constants $C_1, C_2, \ldots, C_8$ are generated in the same way as the constants of the $\ast$ operation and their values (in hexadecimal notation) for different word sizes are given in Table 1.6, Table 1.7, and Table 1.8.
### 1.3 The $\pi$-function

#### Table 1.6: Round constants for $\pi$16-Cipher

<table>
<thead>
<tr>
<th>$C^1$</th>
<th>{0xB4B2, 0xB1AC, 0xAA99, 0xA6A5}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^2$</td>
<td>{0xA39C, 0x9A99, 0x9695, 0x938E}</td>
</tr>
<tr>
<td>$C^3$</td>
<td>{0x8D8B, 0x8778, 0x7472, 0x716C}</td>
</tr>
<tr>
<td>$C^4$</td>
<td>{0x6A69, 0x6665, 0x635C, 0x5A59}</td>
</tr>
<tr>
<td>$C^5$</td>
<td>{0x5655, 0x534E, 0x4D4B, 0x473C}</td>
</tr>
<tr>
<td>$C^6$</td>
<td>{0x3A39, 0x3635, 0x332E, 0x2D2B}</td>
</tr>
<tr>
<td>$C^7$</td>
<td>{0x271E, 0x1D1B, 0x170F, 0xF0E8}</td>
</tr>
<tr>
<td>$C^8$</td>
<td>{0xE4E2, 0xE1D8, 0xD4D2, 0xD1CC}</td>
</tr>
</tbody>
</table>

#### Table 1.7: Round constants for $\pi$32-Cipher

<table>
<thead>
<tr>
<th>$C^1$</th>
<th>{0x8D8B8778, 0x7472716C, 0x6A696665, 0x635C5A59}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^2$</td>
<td>{0x5655534E, 0x4D4B473C, 0x3A393635, 0x332E2D2B}</td>
</tr>
<tr>
<td>$C^3$</td>
<td>{0x271E1D1B, 0x170F0E8, 0xE4E2E1D8, 0xD4D2D1CC}</td>
</tr>
<tr>
<td>$C^4$</td>
<td>{0xCAC9C6C5, 0xC3B8B4B2, 0xB1ACAA99, 0xA6A5A39C}</td>
</tr>
<tr>
<td>$C^5$</td>
<td>{0x9A999695, 0x938E8D8B, 0x87787472, 0x716C5A69}</td>
</tr>
<tr>
<td>$C^6$</td>
<td>{0x6665635C, 0x5A595655, 0x534E4D4B, 0x473C3A39}</td>
</tr>
<tr>
<td>$C^7$</td>
<td>{0x3635332E, 0x2D2B271E, 0x1D1B170F, 0xF0E8E4E2}</td>
</tr>
<tr>
<td>$C^8$</td>
<td>{0xE1D8D4D2, 0xD1CCAC99, 0xC6C5C3B8, 0xB4B2B1AC}</td>
</tr>
</tbody>
</table>

#### Table 1.8: Round constants for $\pi$64-Cipher

<table>
<thead>
<tr>
<th>$C^1$</th>
<th>{0x271E1D1B170F0E8, 0xE4E2E1D8D4D2D1CC, 0xCAC9C6C5C3B8B4B2, 0xB1ACAA99A6A5A39C}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^2$</td>
<td>{0x9A999695938E8D8B, 0x87787472716C5A69, 0x6665635C5A595655, 0x534E4D4B473C3A39}</td>
</tr>
<tr>
<td>$C^3$</td>
<td>{0x3635332E2D2B271E, 0x1D1B170F0E8E4E2, 0xE1D8D4D2D1CCAC99, 0xC6C5C3B8B4B2B1AC}</td>
</tr>
<tr>
<td>$C^4$</td>
<td>{0xAAA9A6A5A39C9A99, 0x9695938E8D8B778, 0x7472716C5A696665, 0x635C5A5956553A4E}</td>
</tr>
<tr>
<td>$C^5$</td>
<td>{0x4D4B473C3A393635, 0x332E2D2B271E1D1B, 0x170F0E8E4E2E1D8, 0xD4D2D1CCAC9C6C5}</td>
</tr>
<tr>
<td>$C^6$</td>
<td>{0xC3B8B4B2B1ACAA99, 0xA6A5A39C9A999695, 0x938E8D8B7787472, 0x716C5A6966653A3C}</td>
</tr>
<tr>
<td>$C^7$</td>
<td>{0x5A9565534E4D4B, 0x473C3A393635332E, 0x2D2B271E1D1B170F, 0xF0E8E4E2E1D8D4D2}</td>
</tr>
<tr>
<td>$C^8$</td>
<td>{0xD1CCAC9C6C5C3B8, 0xB4B2B1ACAA9A6A5, 0xA39C9AA999695938E, 0x8D8B7787472716C}</td>
</tr>
</tbody>
</table>
Table 1.9: An algorithmic description of the ARX operation $*$ for 16–bit words.

<table>
<thead>
<tr>
<th><strong>Operation for 16–bit words</strong></th>
</tr>
</thead>
</table>

**Input:** $X = (X_0, X_1, X_2, X_3)$ and $Y = (Y_0, Y_1, Y_2, Y_3)$ where $X_i$ and $Y_i$ are 16–bit variables.

**Output:** $Z = (Z_0, Z_1, Z_2, Z_3)$ where $Z_i$ are 16–bit variables.

**Temporary 16–bit variables:** $T_0, \ldots, T_{11}$.

**$\mu$–transformation for $X$:**

1. $T_0 \leftarrow ROTL^1(0x0FE8 + X_0 + X_1 + X_2)$;
2. $T_1 \leftarrow ROTL^4(0x4E2 + X_0 + X_1 + X_3)$;
3. $T_2 \leftarrow ROTL^8(0x1DE8 + X_0 + X_2 + X_3)$;
4. $T_3 \leftarrow ROTL^{11}(0xD4D2 + X_1 + X_2 + X_3)$;
5. $T_4 \leftarrow T_0 \oplus T_1 \oplus T_3$;
6. $T_5 \leftarrow T_0 \oplus T_1 \oplus T_2$;
7. $T_6 \leftarrow T_1 \oplus T_2 \oplus T_3$;
8. $T_7 \leftarrow T_0 \oplus T_2 \oplus T_3$;

**$\nu$–transformation for $Y$:**

1. $T_0 \leftarrow ROTL^2(0xD1CC + Y_0 + Y_2 + Y_3)$;
2. $T_1 \leftarrow ROTL^8(0xCAC9 + Y_1 + Y_2 + Y_3)$;
3. $T_2 \leftarrow ROTL^7(0xC6C5 + Y_0 + Y_1 + Y_2)$;
4. $T_3 \leftarrow ROTL^{13}(0xC3B8 + Y_0 + Y_1 + Y_3)$;
5. $T_8 \leftarrow T_1 \oplus T_2 \oplus T_3$;
6. $T_9 \leftarrow T_0 \oplus T_2 \oplus T_3$;
7. $T_{10} \leftarrow T_0 \oplus T_1 \oplus T_3$;
8. $T_{11} \leftarrow T_0 \oplus T_1 \oplus T_2$;

**$\sigma$–transformation for both $\mu(X)$ and $\nu(Y)$:**

1. $Z_3 \leftarrow T_4 + T_8$;
2. $Z_0 \leftarrow T_5 + T_9$;
3. $Z_1 \leftarrow T_6 + T_{10}$;
4. $Z_2 \leftarrow T_7 + T_{11}$;
Table 1.10: An algorithmic description of the ARX operation \( \star \) for 32–bit words.

<table>
<thead>
<tr>
<th>* operation for 32–bit words</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input:</strong> ( X = (X_0, X_1, X_2, X_3) ) and ( Y = (Y_0, Y_1, Y_2, Y_3) ) where ( X_i ) and ( Y_i ) are 32–bit variables.</td>
</tr>
<tr>
<td><strong>Output:</strong> ( Z = (Z_0, Z_1, Z_2, Z_3) ) where ( Z_i ) are 32–bit variables.</td>
</tr>
<tr>
<td><strong>Temporary 32–bit variables:</strong> ( T_0, \ldots, T_{11} ).</td>
</tr>
</tbody>
</table>

\( \mu \)–transformation for \( X \):

1. \( T_0 \leftarrow ROTL^5(0x8D8B8778 + X_0 + X_1 + X_2) \);
2. \( T_1 \leftarrow ROTL^{11}(0x7472716C + X_0 + X_1 + X_3) \);
3. \( T_2 \leftarrow ROTL^{17}(0x6A696665 + X_0 + X_2 + X_3) \);
4. \( T_3 \leftarrow ROTL^{23}(0x635C5A59 + X_1 + X_2 + X_3) \);
5. \( T_4 \leftarrow T_0 \oplus T_1 \oplus T_3 \);
6. \( T_5 \leftarrow T_0 \oplus T_1 \oplus T_2 \);
7. \( T_6 \leftarrow T_1 \oplus T_2 \oplus T_3 \);
8. \( T_7 \leftarrow T_0 \oplus T_2 \oplus T_3 \);

\( \nu \)–transformation for \( Y \):

1. \( T_0 \leftarrow ROTL^3(0x5655534E + Y_0 + Y_2 + Y_3) \);
2. \( T_1 \leftarrow ROTL^{10}(0x4D4B473C + Y_1 + Y_2 + Y_3) \);
3. \( T_2 \leftarrow ROTL^{19}(0x3A393635 + Y_0 + Y_1 + Y_2) \);
4. \( T_3 \leftarrow ROTL^{29}(0x332E2D2B + Y_0 + Y_1 + Y_3) \);
5. \( T_8 \leftarrow T_1 \oplus T_2 \oplus T_3 \);
6. \( T_9 \leftarrow T_0 \oplus T_1 \oplus T_3 \);
7. \( T_{10} \leftarrow T_0 \oplus T_1 \oplus T_2 \);
8. \( T_{11} \leftarrow T_0 \oplus T_2 \oplus T_3 \);

\( \sigma \)–transformation for both \( \mu(X) \) and \( \nu(Y) \):

1. \( Z_3 \leftarrow T_4 + T_8 \);
2. \( Z_0 \leftarrow T_5 + T_9 \);
3. \( Z_1 \leftarrow T_6 + T_{10} \);
4. \( Z_2 \leftarrow T_7 + T_{11} \).
1.3 The $\pi$-function

Table 1.11: An algorithmic description of the ARX operation $\ast$ for 64-bit words.

<table>
<thead>
<tr>
<th>$\ast$ operation for 64-bit words</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input:</strong> $X = (X_0, X_1, X_2, X_3)$ and $Y = (Y_0, Y_1, Y_2, Y_3)$ where $X_i$ and $Y_i$ are 64-bit variables.</td>
</tr>
<tr>
<td><strong>Output:</strong> $Z = (Z_0, Z_1, Z_2, Z_3)$ where $Z_i$ are 64-bit variables.</td>
</tr>
<tr>
<td><strong>Temporary 64-bit variables:</strong> $T_0, \ldots, T_{11}$.</td>
</tr>
<tr>
<td><strong>$\mu$-transformation for $X$:</strong></td>
</tr>
<tr>
<td>$T_0 \leftarrow ROTL^7(0x{F}0E8E4E2E1D8D4D2) + X_0 + X_1 + X_2$;</td>
</tr>
<tr>
<td>$T_1 \leftarrow ROTL^{10}(0x{D}1CCAC9C6C5C3B8) + X_0 + X_1 + X_3$;</td>
</tr>
<tr>
<td>$T_2 \leftarrow ROTL^{31}(0x{B}4B2B1ACAA9A6A5) + X_0 + X_2 + X_3$;</td>
</tr>
<tr>
<td>$T_3 \leftarrow ROTL^{53}(0x{A}39C9A999695938E) + X_1 + X_2 + X_3$;</td>
</tr>
<tr>
<td>$T_4 \leftarrow T_0 \oplus T_1 \oplus T_3$;</td>
</tr>
<tr>
<td>$T_5 \leftarrow T_0 \oplus T_1 \oplus T_2$;</td>
</tr>
<tr>
<td>$T_6 \leftarrow T_1 \oplus T_2 \oplus T_3$;</td>
</tr>
<tr>
<td>$T_7 \leftarrow T_0 \oplus T_2 \oplus T_3$;</td>
</tr>
<tr>
<td><strong>$\nu$-transformation for $Y$:</strong></td>
</tr>
<tr>
<td>$T_0 \leftarrow ROTL^{11}(0x{8}D8B87787472716C) + Y_0 + Y_2 + Y_3$;</td>
</tr>
<tr>
<td>$T_1 \leftarrow ROTL^{23}(0x{6}A96665635C5A59) + Y_1 + Y_2 + Y_3$;</td>
</tr>
<tr>
<td>$T_2 \leftarrow ROTL^{37}(0x{5}655534E4D4B473C) + Y_0 + Y_1 + Y_2$;</td>
</tr>
<tr>
<td>$T_3 \leftarrow ROTL^{59}(0x{3}A393635332E2D2B) + Y_0 + Y_1 + Y_3$;</td>
</tr>
<tr>
<td>$T_8 \leftarrow T_1 \oplus T_2 \oplus T_3$;</td>
</tr>
<tr>
<td>$T_9 \leftarrow T_0 \oplus T_2 \oplus T_3$;</td>
</tr>
<tr>
<td>$T_{10} \leftarrow T_0 \oplus T_1 \oplus T_3$;</td>
</tr>
<tr>
<td>$T_{11} \leftarrow T_0 \oplus T_1 \oplus T_2$;</td>
</tr>
<tr>
<td><strong>$\sigma$-transformation for both $\mu(X)$ and $\nu(Y)$:</strong></td>
</tr>
<tr>
<td>$Z_3 \leftarrow T_4 + T_8$;</td>
</tr>
<tr>
<td>$Z_0 \leftarrow T_5 + T_9$;</td>
</tr>
<tr>
<td>$Z_1 \leftarrow T_6 + T_{10}$;</td>
</tr>
<tr>
<td>$Z_2 \leftarrow T_7 + T_{11}$;</td>
</tr>
</tbody>
</table>
Chapter 2

Security goals

Table 2.1: A list of security goals for the π-Cipher.

<table>
<thead>
<tr>
<th>Goal</th>
<th>Pi16Cipher96v1</th>
<th>Pi16Cipher128v1</th>
<th>Pi32Cipher128v1</th>
<th>Pi32Cipher256v1</th>
<th>Pi64Cipher128v1</th>
<th>Pi64Cipher256v1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidentiality for the plaintext</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>Confidentiality for the secret message number SMN</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>Integrity for the plaintext</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>Integrity for the associated data</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>Integrity for the public message number PMN</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>Integrity for the secret message number SMN</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>Confidentiality for the plaintext $M$, when $(K, AD, (PMN, SMN_1))$ and $(K, AD, (PMN, SMN_2))$</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>Integrity for the plaintext $M$, when $(K, AD, (PMN, SMN_1))$ and $(K, AD, (PMN, SMN_2))$</td>
<td>96</td>
<td>128</td>
<td>128</td>
<td>256</td>
<td>128</td>
<td>256</td>
</tr>
</tbody>
</table>

We want to emphasize our position that the security level of 80 bits should be considered as insecure and should be abandoned in future cryptographic designs. This is
due to the recent reported practical speed of many different computing systems (GPUs, supercomputers, FPGAs). That is why our lowest level for security is 96 bits of security.

Users have two options for nonces in $\pi$-Cipher. A nonce can be $NONCE = PMN$ or $NONCE = (PMN, SMN)$.

If the legitimate key holder uses the same $NONCE$ to encrypt two different pairs of (plaintext, associated data) $(M_1, AD)$ and $(M_2, AD)$ with the same secret key $K$ then the confidentiality and the integrity of the plaintexts are not preserved in $\pi$-Cipher. **Thus, the first six goals in Table 2 are achieved under the assumption that $PMN$ is always different for any two different pairs of (plaintext, associated data) $(M_1, AD)$ and $(M_2, AD)$ with the same secret key $K$.**

Additionally, $\pi$-Cipher offers an intermediate level of robustness when a legitimate key holder uses the same secret key $K$, the same associated data $AD$, the same public message number $PMN$ but different secret message numbers $SMN_1$ and $SMN_2$ for encrypting two different plaintexts $M_1$ and $M_2$. In that case confidentiality and integrity of the plaintexts are preserved. **However, in that case the confidentiality of $SMN_1$ and $SMN_2$ is not preserved.**
Chapter 3

Security analysis

3.1 Bit diffusion analysis

We give a bit diffusion analysis for the $\ast$ operation and for one round of the $\pi$ function of $\pi_{16}$-Cipher, $\pi_{32}$-Cipher and $\pi_{64}$-Cipher.

In our analysis, we have used two experimental settings:

1. Examining the propagation of a one bit difference in a 10000 randomly generated $X$ and $Y$ (inputs) of the $\ast$ operation;

2. Examining the propagation of a one bit difference in a 1000 randomly generated Internal states $IS$ for one round of the $\pi$ function.

We performed several experiments for different word sizes ($\omega = 16, 32, 64$).

In the experimental setting under (1) we generated 10000 random values for $X$ and $Y$. First, we measured what is the Hamming distance between outputs $Z$ and $Z'$ ($Z = X \ast Y$ and $Z' = X' \ast Y$), where 1 bit is changed in the input $X$ ($HammingDist(X, X') = 1$). After that we measured the Hamming distance between outputs $Z$ and $Z'$ of the $\ast$ operation ($Z = X \ast Y$ and $Z' = X \ast Y'$) where 1 bit is changed in $Y$ ($HammingDist(Y, Y') = 1$). The results for $\omega = 16, 32, 64$ are shown in Figure 3.1, Figure 3.2 and Figure 3.3.

In the experimental setting under (2) we generated 1000 random values for the Internal State $IS$ and used just one round of the $\pi$ function. Here we measure the Hamming distance between the outputs ($\pi(IS)$ and $\pi(IS')$), where one bit is changed in the $IS$ ($HammingDistance(IS, IS') = 1$). The results for $\omega = 16, 32, 64$ are shown in Figure 3.4, Figure 3.5 and Figure 3.6.
3.1 Bit diffusion analysis

Figure 3.1: Avalanche effect of the $\ast$ operation for $\omega = 16$

Figure 3.2: Avalanche effect of the $\ast$ operation for $\omega = 32$

Figure 3.3: Avalanche effect of the $\ast$ operation for $\omega = 64$
3.2 Distinguisher for one round $\pi_{16}$-Cipher096 and $\pi_{16}$-Cipher128

We describe a distinguisher attack for one round $\pi_{16}$-Cipher096 and $\pi_{16}$-Cipher128.

Figure 3.4: Avalanche effect of one round of the $\pi$ function where $\omega = 16$ ($Min = 120.732$, $Avg = 127.255$, $Max = 128.731$)

Figure 3.5: Avalanche effect of one round of the $\pi$ function where $\omega = 32$ ($Min = 226.063$, $Avg = 256.765$, $Max = 251.472$)
3.2 Distinguisher for one round $\pi_{16}$-Cipher096 and $\pi_{16}$-Cipher128

Figure 3.6: Avalanche effect of one round of the $\pi$ function where $\omega = 64$ ($\text{Min} = 400.88$, $\text{Avg} = 485.646$, $\text{Max} = 515.76$)

For $\omega = 16$ the size of the part $J_2$ in Figure 3.7 is 64 bits. Thus, by trying all $2^{64}$ values for $J_2$ (the graphical representation is in Figure 3.8) we can obtain in a unique way a list $\mathcal{L}_1 = \{(I_{1i}, I_{2i}) \mid 0 \leq i < 2^{64}\}$ of $2^{64}$ different values for the pairs $(I_{1i}, I_{2i})$ (the graphical representation is in Figure 3.9). We build a similar list $\mathcal{L}_2 = \{(I'_{1i}, I'_{2i}) \mid 0 \leq i < 2^{64}\}$ for the next encrypted block. Knowing that the encryption for the next block is by injecting a counter that was incremented by 1 from the previous counter value, and that it was injected in the position of $I_1$, while the value of $I_2$ was the same, we build a matching list $\mathcal{L}_3 = \{(I_{1i}, I'_{1i}, I_{2i}, I'_{2i}) \mid 0 \leq i < 2^{64}\}$ where $I'_{1i} - I_{1i} = 1$. With probability 1 there will be a pair of values where $I_{2i} = I'_{2i}$, while if the values of $J_1$ and $J_3$ were from an ideal random source, the probability that there will be a pair where $I_{2i} = I'_{2i}$ is very low (much less than $2^{-32}$). In total, the complexity of the attack is $2^{65}$ computations of the operation $\star$, and the space is $2^{65} \times 16 = 2^{69}$ bytes.

For more than one round, or for bigger values of $\omega$, this distinguishing attack is more complex than the claimed security of the cipher.
3.2 Distinguisher for one round $\pi_{16}$-Cipher096 and $\pi_{16}$-Cipher128

Figure 3.7: One round of $\pi_{16}$-Cipher

Figure 3.8: For $J_2$ we try all possible $2^{64}$ values.

Figure 3.9: The blue squares are either guessed ones (that is $J_2$) or obtained in a unique way from the definition of the operation $\ast$. 
Chapter 4

Features

In this chapter we discuss the features of π-Cipher loosely following the structure of the features section [http://competitions.cr.yp.to/features.html] on the CAESAR web site.

Cipher-structure (Encrypt than MAC). First we want to point out that it is relatively straightforward to show that the π-Cipher is an Encrypt-then-MAC authenticated cipher. Let us recall the definition for the Encrypt-then-MAC authenticated cipher: We say that the authenticated cipher is Encrypt-then-MAC if a message $M$ is encrypted under a secret key $K_1$ and then the tag $T$ is calculated with another secret key $K_2$ as $MAC(K_2, C)$. The pair $(C, T)$ is the output of the authenticated encryption procedure.

If we describe the e-triplex component used in π-Cipher in a mathematical form we have the following. First the message $M$ is encrypted producing the ciphertext $C$ as

$$
IS \leftarrow \pi(CIS_{bitrate} \oplus counter \ \ || \ || CIS_{capacity}),
C \leftarrow M \oplus IS_{bitrate}.
$$

Then, the tag $T$ is calculated as

$$
t \leftarrow \pi(C \ \ || \ || IS_{capacity})_{bitrate}.
$$

Here, the value of $CIS_{bitrate} \oplus counter \ || | CIS_{capacity}$ has the role of $K_1$ in the definition of Encrypt-then-MAC, and the value of $C \ || | IS_{capacity}$ has the role of the pair $(K_2, C)$ in the $MAC(K_2, C)$ part of the definition of Encrypt-then-MAC.
**Associated Data and NONCE reuse.** If we encrypt two different plaintexts $M_1$ and $M_2$ with the same secret key $K$, associated data $AD$ and nonce $NONCE = (PMN, SMN)$, then neither the confidentiality nor the integrity of the plaintexts are preserved in the $\pi$–Cipher. However, as one measure to reduce the risks of a complete reuse of the $NONCE$ we have adopted the strategy of a composite $NONCE = (PMN, SMN)$. If either $PMN$ or $SMN$ are different, then both the confidentiality and integrity of plaintexts are preserved.

**Plaintext corruption, associated-data corruption, message-number corruption, ciphertext corruption.** We posit that the $\pi$-Cipher can straightforwardly be proven INT-CTXT secure under the assumption that the permutation $\pi$ is an ideal random permutation without any structural distinguishers, by adapting the proof of the XOR-MAC scheme [1]. This is due to the close resemblance of the tag-generation part of the $\pi$-Cipher with the XOR-MAC.

**Ciphertext prediction.** The best distinguishing attack that we know for the $\pi$-Cipher is for the versions $\pi$16-Cipher096 and $\pi$16-Cipher128 with just one round and is described in Section 3.2. The complexity of the attack is $2^{65}$ computations of the operation $\ast$, and the space is $2^{65} \times 16 = 2^{69}$ bytes.

**Replay and reordering.** For the $\pi$-Cipher, the standard defense against both replay and reordering is for the sender to use strictly increasing public message numbers $PMNs$, and for the receiver to refuse any message whose message number is no larger than the largest number of any verified message. This requires both the sender and receiver to keep state.

**Sabotage.** The $\pi$-Cipher puts the encryption of the $SMN$ value as the first block of the ciphertext $C$. Thus, in protocols that use the $\pi$-Cipher, the receiver can make an early reject of invalid messages by decrypting the first block (containing the SMN) and comparing it to its expected value. Only if this check passes the receiver continues with the rest of the decryption and tag computation. Note however, that this requires the protocol to not return error messages to the sender, in order to avoid timing attacks. AES-GCM does not have this property.
Plaintext espionage. Since the attacker’s goal here is to figure out the user’s secret message, the only feasible attack can happen when the size of the secret message is small by building a table of encrypted secret messages. To defend against this attack the $\pi$-Cipher requires the nonce pair $NONCE = (PMN, SMN)$ to have a unique value for every encryption.

Message-number espionage. In the $\pi$-Cipher there is a dedicated phase for encrypting the secret message number $SMN$, and figuring out the value of $SMN$ is equivalent to breaking the whole cipher which is infeasible under the assumptions that the permutation $\pi()$ is random.

General input scheduling. The $\pi$-Cipher can offer two ways for reducing the latency: (1) If the key $K$ and the public message number $PMN$ are known in advance and used repeatedly, then it is possible to precompute phase 1. and store the resulting Common Internal State (CIS) for subsequent applications of the cipher. (2) If the key $K$, the public message number $PMN$ and the associated data $AD$ are known in advance and used repeatedly, then it is possible to precompute both phase 1. and phase 2. for subsequent uses. In both cases, in order to preserve the confidentiality and the integrity of the plaintext, for every encryption the secret message numbers $SMN$’s must be unique.

Incrementality. The $\pi$-Cipher is an incremental authenticated cipher. Unlike AES-GCM which also has the incrementality property, the $\pi$-Cipher computes the incremented tag with a constant number of operations regardless of the relative position of the changed plaintext block in the whole encrypted plaintext.

Tag second preimage resistance - resistance against finding second preimage for an authentication tag when the key is known (insider attack). $\pi$-Cipher offers some level of tag second-preimage resistance. We say some level, since the computational efforts for finding a second-preimage for a given pair $(message, tag)$ are not the same as for finding second-preimages for hash functions. And if the $\pi$-Cipher is used for authenticated encryption of messages with arbitrary length (in the framework of the maximally allowed size of the messages which is up to $2^{64}$ bytes), as it was shown by Leurent in [6] the tag second-preimages can be computed with complexities from $2^{22}$ using messages that are long $2^{11}$ blocks up to complexity $2^{45}$ using messages that are
long $2^{22}$ blocks. Laurent’s analysis on $\pi$-Cipher v1 was based on Wagner’s generalized birthday attack \[8\] which complexity can be described as follows. The complexity of finding a preimage message $M = M_1||M_2||\ldots||M_K$ of $K$ blocks, where $K$ is smaller than some predefined big number, is:

$$\min_K O(2^{\frac{K}{2}})$$  \hspace{1cm} (4.1)

If the length of the messages is not restricted, then the minimum in equation (4.1) is achieved for messages of $K = 2\sqrt{K} - 1$ blocks.

However, there are situations when we need to encrypt relatively short messages. For example, if we use the $\pi$-Cipher in IPSec or TLS with the most common Internet packet size of 1500 bytes, then for $\pi$64-Cipher128 or $\pi$64-Cipher256 the encrypted messages will have “just” 24 packets. In that case the Wagner’s generalized birthday attack in order to find a second-preimage for a given tag will need $2^{108}$ e-triplex invocations and a space of $2^{113}$ bytes. We note that by choosing different values for the tweakable parameter $N$, we can achieve different levels of tag second-preimage resistance.

**Software performance.** For efficient software implementations, we propose to use the $\pi$64-Cipher. On modern Intel CPUs (Sandy Bridge and Haswell) the initial and slightly optimized implementation (but non-SIMD) achieves the speeds from 6.5 cpb up to 12 cpb.

**Lightweight hardware performance.** For a lightweight hardware implementation we propose to use the $\pi$16-Cipher. Our initial and slightly optimized implementation of the basic operation $\ast$ on FPGA Xilinx Virtex6-XC6VLX240T needs 41 slices and two RAM blocks.
Chapter 5

Design rationale

Disclaimer: "The designer/designers have not hidden any weaknesses in this cipher."

5.1 Why parallelism, incrementality and tag second-preimage resistance?

While AES-GCM can be parallelized and can be used to perform incremental updates of the ciphertext and the tag, it is not a tag second-preimage resistant. In our presentation at DIAC 2013 [4] we located several reasons why MACs should retain some hash properties when the key is known. We argued that since the Robustness is one of the main goals of the future AEAD standard, tag second-preimage resistance should be one of the features that an AEAD cipher should posses. We also gave two realistic scenarios ("Secure audit logs" and Multi-cast authentication) when the lack of tag second-preimage resistance in authenticated encryption can be exploited.

While the proposed sponge constructions of authenticated encryption offer tag second-preimage resistance, they lack some of the properties that are also useful and desired (such as parallelizability and incrementality). As a result of this line of reasoning, we designed a cipher for authenticated encryption that is parallel, incremental and offers a certain level of tag second-preimage resistance.
5.2 Why constants in \(\pi\)-Cipher and how to choose them

In order to avoid the existence of some trivial fixed points in the permutation function \(\pi\), we decided to use constants in the affine bijective transformations \(\hat{A}_1\) and \(\hat{A}_3\) from the \(\mu\) and \(\nu\) permutations. The reason why we choose these constants is that they are represented as a sequence of equal distribution of 0s and 1s. Having these constants in \(\hat{A}_1\) and \(\hat{A}_3\) we are not aware of any point \(X\) such that

\[
\pi(X) = X.
\]

The size and value of the constants depend on the length of the words in the \(\pi\)-Cipher. First we generate the set \(\text{Constants}\) of all possible 8-bit (1 byte) candidates with equal distribution of 0s and 1s in their binary representation. The total number of elements in this set is 70, and is given by:

\[
\text{Constants} = \{0xF0, 0xE8, 0xE4, 0xE2, 0xE1, 0xD8, 0xD4, 0xD2, 0xD1, 0xCC, 0xCA, 0xC9, 0xC6, 0xC5, 0xC3, 0xB8, 0xB4, 0xB2, 0xB1, 0xAC, 0xAA, 0xA9, 0xA6, 0xA5, 0xA3, 0x9C, 0x9A, 0x99, 0x96, 0x95, 0x93, 0x8E, 0x8D, 0x8B, 0x87, 0x78, 0x74, 0x72, 0x71, 0x6C, 0x6A, 0x69, 0x66, 0x65, 0x63, 0x5C, 0x5A, 0x59, 0x56, 0x55, 0x53, 0x4E, 0x4D, 0x4B, 0x47, 0x3C, 0x3A, 0x39, 0x36, 0x35, 0x33, 0x2E, 0x2D, 0x2B, 0x27, 0x1E, 0x1D, 0x1B, 0x17, 0x0F\}
\]

The constants used in the \(\pi\omega\)-Ciphers with different word sizes consist of a concatenation of a consecutive 8-bit elements from the set \(\text{Constants}\).

\(\pi16\)-Cipher uses eight 16-bit constants for the \(\ast\) operation and eight 4-tuples of 16-bit constants for the rounds. We start from the first element of the set 0xF0 and take 16 successive byte values up to the value 0xB8 and form the constants for the \(\ast\) operation. After that, we take every eight successive byte values to form one round constant. We repeat this procedure 8 times and generate the constants \(C_1, C_2, \ldots, C_8\) for the rounds.

Since \(\pi32\)-Cipher uses eight 32-bit constants for the \(\ast\) operation and eight 4-tuples of 32-bit constants for the rounds, we take 32 successive byte values starting from the
first one 0xF0 and form the constants for the \( \ast \) operation. The next 128 consecutive byte values are used for generating constants for the rounds. Because we need 128 bytes for the round constants of \( \pi_{32} \)-Cipher and have 70 elements in the set, for the 71st byte we take the value of the first element in the set \( Constants \) again.

\( \pi_{64} \)-Cipher uses eight 64-bit constants for the \( \ast \) operation. They are taken as 64 successive byte values from the set, starting from the first one 0xF0. Since \( \pi_{64} \)-Cipher uses 4-tuples of 8 bytes round constants, we take them successively starting from the value 0x27 in the set \( Constants \).

The values of both constants (for the \( \ast \) operation and for rounds) for different \( \pi \)-Ciphers are given in Section 1.3.
Chapter 6

Intellectual property

We, the designers of the π-Cipher hereby declare that, to the best of our knowledge, the design of the algorithm that we have submitted for the CAESAR competition, is not covered by any patents. We also hereby declare that we intend never to cover the design of the π-Cipher by any patent.

If any of this information changes, the submitter/submitters will promptly (and within at most one month) announce these changes on the crypto-competitions mailing list.
Chapter 7

Consent

The submitter/submitters hereby consent to all decisions of the CAESAR selection committee regarding the selection or non-selection of this submission as a second-round candidate, a third-round candidate, a finalist, a member of the final portfolio, or any other designation provided by the committee. The submitter/submitters understand that the committee will not comment on the algorithms, except that for each selected algorithm the committee will simply cite the previously published analyses that led to the selection of the algorithm. The submitter/submitters understand that the selection of some algorithms is not a negative comment regarding other algorithms, and that an excellent algorithm might fail to be selected simply because not enough analysis was available at the time of the committee decision. The submitter/submitters acknowledge that the committee decisions reflect the collective expert judgments of the committee members and are not subject to appeal. The submitter/submitters understand that if they disagree with published analyses then they are expected to promptly and publicly respond to those analyses, not to wait for subsequent committee decisions. The submitter/submitters understand that this statement is required as a condition of consideration of this submission by the CAESAR selection committee.
References


