

# FPGA-Based Key Generator for Post-Quantum Key Encapsulation Based on Quasi-Cyclic Codes

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**Abstract.** In this paper, we present a constant-time FPGA-based key generator for a quantum-safe key encapsulation mechanism based on MDPC codes called BIKE, which is among round-2 candidates in the NIST PQC standardization process. Existing hardware implementations of MDPC code-based systems focus on the encryption/decryption (key encapsulation/decapsulation) operations while few of them take into account the key generation operation which is particularly crucial for KEM-based applications. The hardware architecture for the key generator proposed in this work aims at maximizing the metric of timing efficiency while maintaining a low resource consumption. Parallelized polynomial multiplication and squaring algorithms are proposed and implemented to achieve this goal. Our experimental results show that our key generator design requires  $9.5 \times 10^5$  cycles (0.597 ms),  $2.1 \times 10^6$  cycles (14.334 ms) and  $9.8 \times 10^5$  cycles (0.492 ms) respectively to generate a key pair for BIKE-1/2/3. The proposed key generator is very area-efficient, it uses only 544/1272/423 slices for BIKE-1/2/3 on a small-sized low-end Xilinx Spartan-7 FPGA.

**Keywords:** Post-Quantum Cryptography, Key Encapsulation Mechanism, Key Generator, QC-MDPC Code, FPGA Implementation

## 1 Introduction

Key encapsulation mechanisms (KEMs) are commonly used encryption techniques to secure the transmission of symmetric cryptographic keys by use of public-key cryptographic algorithms. Therefore, efficient and secure KEM designs have always been an important topic in the cryptographic community. In the past few years, NIST has started the PQC standardization process soliciting the designs of efficient and secure post-quantum KEMs [8] since the construction of a commercial quantum computer emerges as an urgent threat to the commonly used cryptographic primitives nowadays. These primitives rely on the hardness of the integer factorization problem or discrete logarithm problems, e.g., the Diffie-Hellman key exchange, the Rivest-Shamir-Adleman (RSA) and Elliptic Curve Cryptography (ECC). However, in 1994 Shor's algorithm [35] was proposed which can be deployed on a quantum computer and solve both the integer factorization problem and the discrete logarithm problem in polynomial time, and therefore will render the security of the modern cryptographic primitives.

Code-based cryptosystems, which build their security on the hardness of decoding general linear codes, are among the most promising quantum-secure candidates for which no known polynomial time attacks exist by use of a quantum computer. McEliece proposed the first code-based cryptosystem in 1978 [28], which uses binary Goppa codes [18] in the underlying coding system. However, Goppa code-based schemes yield large public keys which limit the deployment of these systems in resource-constrained scenarios. Niederreiter proposed in 1986 a variant of the McEliece cryptosystem [32] which introduced a trick to reduce the size of the public key, namely the Niederreiter cryptosystem. It has been proven that the Niederreiter cryptosystem and the McEliece cryptosystem achieve the same security level [25] when the same family of codes is used.

Active research has been focused on replacing Goppa codes with other families of structured codes for reducing the key size. Nevertheless, many of these attempts lead to the compromise of the the system security. For example, many McEliece variants based on low-density parity-check (LDPC) codes [31], quasi-cyclic low-density parity-check (QC-LDPC) codes [34], quasi-dyadic (QD) codes [29], convolutional codes [27], generalized Reed-Solomon (GRS) codes [4], and rank-metric codes [26, 15] have been successfully broken. However, a few variants exploiting the quasi-cyclic form of the codes [3, 5, 30] have been shown to counteract all the existing cryptanalysis attacks while maintaining small-sized keys. A variety of KEMs built on the Niederreiter cryptosystem and LDPC/MDPC codes such as LEDAkem [2], CAKE [6] and BIKE [1] are proposed and analyzed in the literature. Among these proposals, BIKE is currently among the round-2 candidates for the NIST PQC standardization process. Recently, a new statistical attack, called reaction attack [14, 19] has been devised to recover the key by exploiting the information leaked from decoding failures in QC-LDPC and QC-MDPC code-based systems. This attack is further enhanced in [33] where the error pattern chaining method is introduced to generate multiple undecodable error patterns from an initial error pattern, thus improving the performance of such reaction attack in the CPA case. However, the reaction attack only works for CPA systems and long-term keys, therefore, the deployment of a CCA2-secure conversion or ephemeral keys in BIKE can resist the attack.

**Contributions.** Most of the existing work on hardware implementations of MDPC code-based cryptosystems focus on the encryption and decryption operations. However, KEMs are gradually getting more commonly used in ephemeral key encapsulation scenarios in which cases the key generation is used as often as the encapsulation and decapsulation operations and therefore should also be accelerated by dedicated hardware modules. Therefore, in this work we present the first constant-time, efficient and compact FPGA-based key generator for a promising MDPC code-based post-quantum KEM — BIKE. Our contributions include:

- The proposal of new polynomial arithmetic algorithms (squaring, generic polynomial multiplication and sparse polynomial multiplication) over ring  $\mathbb{F}_2[x]/\langle x^r + 1 \rangle$ .

- Constant-time and efficient hardware architectures for the polynomial arithmetics in  $\mathbb{F}_2[x]/\langle x^r + 1 \rangle$  including polynomial inversion, polynomial squaring, polynomial multiplications and polynomial generation.
- Novel and lightweight hardware architectures for the key generator of three BIKE variants of security ranging between 128-bit and 256-bit.

## 2 Preliminaries

In the following, we describe the basic notations and definitions in QC-MDPC codes which closely follow the descriptions in [1]. Quasi-cyclic (QC) codes can be defined over either matrices or polynomial rings. We use both the matrix view and the polynomial view to describe the relevant aspects of the BIKE scheme.

### 2.1 General Definitions

Table 1 shows the notations used in the following discussions.

Polynomial View:	
$\mathbb{F}_2$	Finite field of 2 elements
$\mathcal{R}$	The cyclic polynomial ring $\mathbb{F}_2[x]/\langle x^r + 1 \rangle$
$ x $	The Hamming weight of a binary polynomial $x$
$u \xleftarrow{\$} U$	Variable $u$ is sampled uniformly at random from set $U$
Matrix View:	
$\mathcal{V}$	The vector space of dimension $n$ over $\mathbb{F}_2$
$\mathbf{m}$	The vector over $\mathbb{F}_2$
$\mathbf{G}$	The matrix over $\mathbb{F}_2$

Table 1: Notations

The basic structure in QC codes is the circulant matrix, which is defined as follows:

**Definition 1.** (*Circulant Matrix*) Let  $\mathbf{x} = (x_0, \dots, x_{n-1}) \in \mathbb{F}_2^n$ . The circulant matrix induced by  $\mathbf{x}$  is defined and denoted as follows:

$$\mathbf{rot}(\mathbf{x}) = \begin{bmatrix} x_0 & x_{n-1} & \cdots & x_1 \\ x_1 & x_0 & \cdots & x_2 \\ \vdots & \vdots & \ddots & \vdots \\ x_{n-1} & x_{n-2} & \cdots & x_0 \end{bmatrix}$$

Therefore, the product of any two polynomials  $x$  and  $y$  in  $\mathcal{R}$  can be viewed as a vector-matrix (or matrix-vector) product using the operator  $\mathbf{rot}(\cdot)$  as:

$$x \cdot y = \mathbf{x} \cdot \mathbf{rot}(\mathbf{y})^T = \mathbf{y} \cdot \mathbf{rot}(\mathbf{x})^T = y \cdot x$$

MDPC codes are a special variant of linear codes and are defined as follows:

**Definition 2.** (*Linear Code*) A Binary Linear Code  $\mathcal{C}$  of length  $n$  and dimension  $k$  (denoted as  $[n, k]$ ) is a subspace of  $\mathcal{V}$  of dimension  $k$ . Elements of  $\mathcal{C}$  are referred to as codewords.

**Definition 3.** (*Generator and Parity-Check Matrix*)  $\mathbf{G} \in \mathbb{F}^{k \times n}$  is a Generator Matrix for the  $[n, k]$  code  $\mathcal{C}$  iff

$$\mathcal{C} = \{\mathbf{m}\mathbf{G} | \mathbf{m} \in \mathbb{F}_2^k\}$$

$\mathbf{H} \in \mathbb{F}^{(n-k) \times n}$  is called a Parity-Check Matrix of  $\mathcal{C}$  iff

$$\mathcal{C} = \{\mathbf{c} \in \mathbb{F}_2^n | \mathbf{H}\mathbf{c}^T = 0\}$$

A linear code can be quasi-cyclic according to the following definition:

**Definition 4.** (*Quasi-Cyclic Codes*) A binary quasi-cyclic (QC) code of index  $n_0$  and order  $r$  is a linear code which admits as generator matrix a block-circulant matrix of order  $r$  and index  $n_0$ . A  $(n_0, k_0)$ -QC code is a quasi-cyclic code of index  $n_0$ , length  $n_0r$  and dimension  $k_0r$

For instance, the generator matrix of a  $(3, 1)$ -QC code is formed by three circulant blocks  $\mathbf{G}_i$ :  $\mathbf{G} = [\mathbf{G}_0 | \mathbf{G}_1 | \mathbf{G}_2]$ .

In the polynomial view, each block  $\mathbf{G}_i$  can be represented (one-to-one mapping) as a polynomial  $g_i$  over  $\mathcal{R}$  and thus the generator matrix  $\mathbf{G}$  can be viewed as the polynomial matrix  $[g_0 | g_1 | g_2]$  over  $\mathcal{R}$ . In all aspects, any codeword  $\mathbf{c} = \mathbf{m} \cdot \mathbf{G}$  over  $\mathbb{F}^n$  can be represented in its polynomial form as  $[mg_0 | mg_1 | mg_2]$  over  $\mathcal{R}$ . All the above notations are collected in Table 1.

## 2.2 BIKE

BIKE was proposed by Aragon *et. al* in 2017 [1], which is a novel code-based key encapsulation mechanism based on QC-sMDPC codes. The use of a QC-MDPC code  $C(n_0, k_0)$  in BIKE brings a big key size reduction compared to unstructured codes. BIKE uses the double-circulant structure for the parity check matrix where two smaller cyclic matrices are included. Nine instances of BIKE (BIKE-1, BIKE-2, BIKE-3) are proposed in their specification. BIKE-1 is a variant which provides fast key generation by using a variation of the McEliece cryptosystem. A preliminary version of BIKE-1 first appeared in [6]. BIKE-2 follows Niederreiter's framework by use of a systematic parity check matrix which can yield a very compact formulation. The BIKE-3 variant follows the work of Ouroboros [11], featuring fast, inversion-less key generation operations. The main difference in BIKE-3 is that the decapsulation invokes the decoding algorithm on a noisy syndrome. This also suggests that BIKE-3 is fundamentally distinct from BIKE-1 and BIKE-2 in terms of security aspects. Parameters for these BIKE instances are shown in Table 2, which covers the 5 security categories suggested by the NIST PQC standardization process. QC construction of the codes brings a significant reduction in memory storage required for public keys, since only

Table 2: Parameters for BIKE, referenced from [1]

Category		n	r	w	t	SL	DFR
1	BIKE-[1,2]	20,326	10,163	142	134	$128 \leq 10^{-7}$	
	BIKE-3	22,054	11,027	134	154		
2-3	BIKE-[1,2]	39,706	19,853	206	199	$192 \leq 10^{-7}$	
	BIKE-3	43,366	21,683	198	226		
4-5	BIKE-[1,2]	65,498	32,749	274	264	$256 \leq 10^{-7}$	
	BIKE-3	72,262	36,131	266	300		

the first row/column of each circulant block needs to be stored and the remaining part can be reconstructed by cyclic rotations of the first row/column, thus largely minimizing the public key size.

The key generation algorithms of BIKE-1/2/3 are described in the following text. Algorithm 1 describes the key generation algorithm of BIKE-1. The private keys comprise of two “sparse” polynomials  $h_0$  and  $h_1$  where  $|h_0|$  and  $|h_1|$  is restricted to  $w/2$ . The public keys  $(f_0, f_1)$  are exposed for public use and therefore must be scrambled to hide the structure of  $h_0$  and  $h_1$ . This is done by multiplying  $h_0$  and  $h_1$  by a random dense polynomial  $g$  to get  $gh_0$  and  $gh_1$ .

**Input:**  $\lambda$ , the target quantum security level.

**Output:** the sparse private key  $\mathbf{PK} = (h_0, h_1)$  and the dense public key  $\mathbf{SK} = (f_0, f_1)$

- 1 Given  $\lambda$ , set the parameters  $r, w$  as described above
- 2 Generate  $h_0, h_1 \leftarrow \mathcal{R}$  both of (odd) weight  $|h_0| = |h_1| = w/2$
- 3 Generate  $g \leftarrow \mathcal{R}$  of odd weight (so  $|g| \approx r/2$ )
- 4 Compute  $(f_0, f_1) \leftarrow (gh_1, gh_0)$
- 5 **return**  $PK$  and  $SK$

**Algorithm 1:** BIKE-1 key generation algorithm in polynomial view [1]

**Input:**  $\lambda$ , the target quantum security level.

**Output:** the sparse private key  $\mathbf{PK} = (h_0, h_1)$  and the dense public key  $\mathbf{SK} = h$

- 1 Given  $\lambda$ , set the parameters  $r, w$  as described above
- 2 Generate  $h_0, h_1 \leftarrow \mathcal{R}$  both of (odd) weight  $|h_0| = |h_1| = w/2$
- 3 Compute  $h \leftarrow h_1 h_0^{-1}$
- 4 **return**  $PK$  and  $SK$

**Algorithm 2:** BIKE-2 key generation algorithm in polynomial view [1]

Algorithm 2 describes the BIKE-2 key generation algorithm. Note that BIKE-2 does not generate any random polynomial to hide the secret keys  $h_0$  and  $h_1$ . Instead, it computes  $h = h_0^{-1}h_1$  as the public key. Therefore, the public key

<p><b>Input:</b> <math>\lambda</math>, the target quantum security level.</p> <p><b>Output:</b> the sparse private key <math>\mathbf{PK} = (h_0, h_1)</math> and the dense public key <math>\mathbf{SK} = (f_0, f_1)</math></p> <ol style="list-style-type: none"> <li>1 Given <math>\lambda</math>, set the parameters <math>r, w</math> as described above</li> <li>2 Generate <math>h_0, h_1 \leftarrow \mathcal{R}</math> both of (odd) weight <math> h_0  =  h_1  = w/2</math></li> <li>3 Generate <math>g \leftarrow \mathcal{R}</math> of odd weight (so <math> g  \approx r/2</math>)</li> <li>4 Compute <math>(f_0, f_1) \leftarrow (h_1 + gh_0, g)</math></li> <li>5 <b>return</b> <math>PK</math> and <math>SK</math></li> </ol>
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**Algorithm 3:** BIKE-3 key generation algorithm in polynomial view [1]

size is halved, however, the computational cost increases due to the required polynomial inversion operation.

Algorithm 3 describes the key generation algorithm of BIKE-3, which is an improved version of BIKE-1. BIKE-3 uses only one multiplication and one addition to compute the first half of public key  $f_0 = h_1 + gh_0$ . The second half  $f_1$  equals to the random dense polynomial  $g$ .

### 3 Polynomial Arithmetics

In this section, we introduce the basic polynomial arithmetics in  $\mathbb{F}_2[x]/(x^r + 1)$  for building the BIKE key generation architecture. Algorithms and implementations for polynomial squaring and multiplications, polynomial inversion, and generation of sparse/dense polynomials with prescribed Hamming weight are presented in the following sub-sections.

**Polynomial Representations.** In this paper, two formats are used to represent polynomials in the quotient ring  $\mathbb{F}_2[x]/(x^r + 1)$ . One is the dense format which stores all the coefficients of a given polynomial  $f = f_0 + f_1x + \dots + f_{r-1}x^{r-1}$ . This format is used when the polynomial is dense, e.g., the public keys  $(f_0, f_1)$  are dense polynomials and therefore are described in this format. In our design, the coefficients of the polynomials are stored in block RAMs, in which each address keeps multiple coefficients as a word. Small endian notation is used here, *i.e.*,  $f_0$  is first stored, then  $f_1$ , and finally  $f_{r-1}$ . We define such data structure for a polynomial  $f$  as  $\bar{\mathbf{f}}$  where  $\bar{\mathbf{f}}[i]$  denotes the word ( $d$  bits in total) stored in the  $i$ -th address as:  $(f_{id}, f_{id+1}, \dots, f_{id+d-1})_2$ . By using this format, in total  $\lceil r/d \rceil$  words are needed to represent a polynomial over  $\mathbb{F}_2[x]/(x^r + 1)$ . For the last word  $\bar{\mathbf{f}}[\lceil r/d \rceil - 1]$ , we append a few zeros to fill it as a complete word:  $(f_{(\lceil r/d \rceil - 1)d}, \dots, f_r, \dots, 0)_2$ . Figure 1a illustrates the data structure of  $\bar{\mathbf{f}}$ .

The other format is the sparse format which is used when the polynomial is sparse, e.g., the secret keys  $(h_0, h_1)$ . This format only saves the bit positions of non-zero coefficients in a polynomial  $f$ . We define this sparse form for a polynomial  $f$  as  $\hat{\mathbf{f}}$  where  $\hat{\mathbf{f}}[i]$  denotes the non-zero bit position (belongs to the set  $\{i | f_i = 1\}$ , each item of this set is  $\log_2(r)$  bits) stored in the  $i$ -th address. This format is memory-efficient especially when the weight of  $f$  is small: It takes

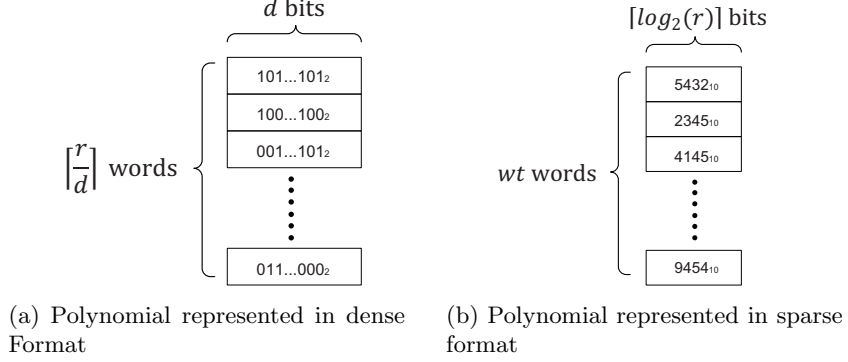


Fig. 1: Polynomial in  $\mathbb{F}_2[x]/(x^r + 1)$  represented in different formats

$|f|$  words and each word is of  $\log_2(r)$  bits to represent a given polynomial  $f$ . Figure 1b illustrates the data structure of  $\hat{\mathbf{f}}$ .

### 3.1 Polynomial Squaring

In this paper, the general squaring form  $(a(x))^{2^n}$  is considered. The following theorem states how to calculate the squaring of a polynomial over  $\mathcal{R}$ .

**Theorem 1.** *For squaring  $(a(x))^{2^n} = \sum \tilde{a}_i x^i$  of a polynomial  $a(x) = \sum a_i x^i \in \mathcal{R}$ , each coefficient  $\tilde{a}_i$  is updated by  $a_j$  in  $[a_{r-1}, a_{r-2}, \dots, a_0]$  as:*

$$\tilde{a}_i = a_{i2^{-n} \bmod r}$$

Note that the data is typically processed word by word on hardware, *i.e.*, only one or two words (in our design, one word is  $d$ -bits) per time are fetched from the memory and loaded to the core function for further calculations. However, sometimes we want to work on one particular bit in the word. Squaring is such an example where bit by bit computations are needed. To preserve the constant-time feature during executions while avoiding the performance degradation in timing, a Barrel shifter is used to rotate the desired bit within  $\lceil \log_2 d \rceil$  cycles. Barrel shifter can be built by pure combinational logic (shown in Fig. 2a) or sequential logic (shown in Fig. 2b). The sequential logic structure optimizes the critical path delay and is used in our design. By doing this, the computational steps for squaring  $(a(x))^{2^n}$  are constant and independent of the value of  $n$ .

Figure 3a depicts the pipeline stages for computing the polynomial squaring operations continuously. The basic computation pattern is: First  $a_{i2^{-n}}$  is read out from the memory, then it gets loaded to the Barrel shifter and rotated to the correct bit position. Finally the result is written back to the memory. In

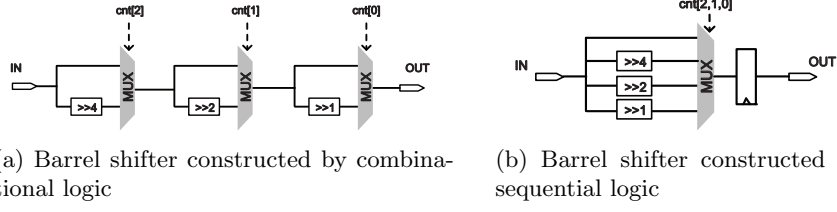


Fig. 2: Barrel shifter used in our key generator to ensure constant execution of multiplication and squaring

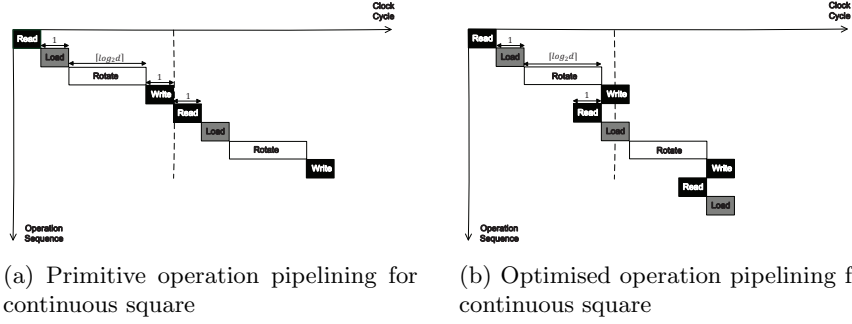


Fig. 3: Timing diagram used in continuous square

general, such pattern repeats  $r$  times and hence the cycle count for computing the squaring operation continuously is:

$$r(\lceil \log_2 d \rceil + 3)$$

We further optimized the above pipeline based on the observation that read and rotation operations can be parallelized, and load and write can be parallelized as well, the pipeline stages are shown in 3a. After this optimization, for computing the squaring operation continuously, we achieve a cycle count of:

$$r(\lceil \log_2 d \rceil + 1) + 2$$

### 3.2 Generic Polynomial Multiplication

A generic polynomial multiplication involves two random dense polynomials. For two dense polynomials  $a(x)$  and  $b(x)$ , their multiplication is represented as:

$$a(x) \cdot b(x) = (a_{r-1}x^{r-1} + \dots + a_1x + a_0) \cdot (b_{r-1}x^{r-1} + \dots + b_1x + b_0) \quad (1)$$

$$= \widetilde{c_{r-1}}x^{r-1} + \widetilde{c_{r-2}}x^{r-2} + \dots + \widetilde{c_1}x + \widetilde{c_0} \quad (2)$$

For software implementations [10, 12], the best practice is to apply a carry-less Karatsuba algorithm to improve the performance for sufficiently high-degree



polynomial multiplications, in particular those used for BIKE and other QC-MDPC code related cryptosystems. Carry-less Karatsuba algorithm is efficient on modern general-purpose processors equipped with “carry-less multiplication” instruction PCLMULQDQ. This instruction computes the product of two binary polynomials of degree 63 and thus an appropriate software flow can use PCLMULQDQ to perform the carry-less Karatsuba algorithm for polynomials with any degree. However, FPGAs do not have similar embedded instructions and moreover, the control flow of Karatsuba algorithm is much more complex and will degrade the timing performance on FPGAs. These issues drive us to search for a better solution for polynomial multiplications on FPGAs.

<p><b>Input:</b> dense polynomials <math>a(x), b(x) \in \mathbb{F}_2[x]/(x^r + 1)</math>.  <b>Output:</b> <math>a(x) \cdot b(x) \in \mathbb{F}_2[x]/(x^r + 1)</math></p> <pre> 1 Reformulate <math>a(x)</math> to block matrix view as <math>A[0], A[1], A[2], \dots, A[n-1]</math> where   <math>n = \lceil r/d \rceil</math>, <math>d</math> is the number of bits used in the row vector <math>A[i]</math>. 2 Compute partial blocks from the transformation matrix <math>BT_{mul}</math> associated with   <math>b(x)</math>: <math>BT_{mul}[0, 0], BT_{mul}[0, 1], BT_{mul}[0, 2], \dots, BT_{mul}[0, n-1]</math> and <math>BT_{mul}[1, 0],</math>   <math>BT_{mul}[2, 0], \dots, BT_{mul}[n-1, 0]</math> 3 The multiplication result is presented again in block matrix view   <math>C[0], C[1], C[2], \dots, C[n-1]</math> 4 /*Diagonal Computation*/ 5 for <math>i \leftarrow 0</math> to <math>n-1</math> do 6   <math>C[i] \leftarrow A[i] \cdot BT_{mul}[0, 0]</math> 7 /*Upper Triangle Computation*/ 8 for <math>i \leftarrow 1</math> to <math>n-1</math> do 9   for <math>j \leftarrow 0</math> to <math>n-1-i</math> do 10    <math>C[i+j] \leftarrow C[i+j] + A[j] \cdot BT_{mul}[0, i]</math> 11 /*Lower Triangle Computation*/ 12 for <math>i \leftarrow 1</math> to <math>n-1</math> do 13   for <math>j \leftarrow 0</math> to <math>n-1-i</math> do 14    <math>C[j] \leftarrow C[j] + A[i+j] \cdot BT_{mul}[i, 0]</math> 15 return the vector <math>C = [C[0], C[1], \dots, C[n-1]]</math> as the coefficients of     <math>c(x) = a(x)b(x)</math> </pre>
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**Algorithm 4:** Proposed generic multiplication algorithm

A formal description of the proposed generic multiplication algorithm can be found in Algorithm 4. As we can see, this algorithm is computed in exactly  $n^2$  steps with  $n = \lceil r/d \rceil$ , and therefore, for fixed BIKE parameters  $r$  and  $d$ , the computational time is also fixed. The core function in the generic polynomial multiplication is the multiplication of a  $d$ -bit vector  $A[k]$  of  $a(x)$  and a block

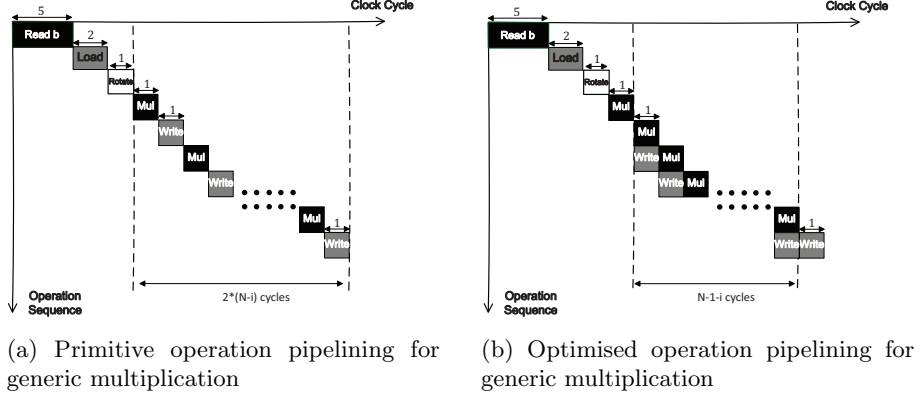


Fig. 4: Timing diagram used in generic multiplication

matrix  $BT_{mul}[i, j]$  from  $BT_{mul}$ :

$$[a_j, a_{j+1}, \dots, a_{j+d-1}] \cdot \begin{bmatrix} b_i & b_{i+1} & b_{i+2} & \cdots & b_{i+d-1} \\ b_{i-1} & b_i & b_{i+1} & \cdots & b_{i+d-2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{i-d+1} & b_{i-d+2} & b_{i-d+3} & \cdots & b_i \end{bmatrix}_{d \times d}$$

We design a dedicate hardware core for the above multiplication which can be finished in one clock cycle, as depicted in Figure 5. With this module, the proposed generic multiplication algorithm can be scheduled as shown in Figure 4a. Read takes 5 cycles to balance the critical path for reading  $B[i, j]$ . A dual-port RAM is used such that the target vector  $B[i, j]$  can be loaded within two cycles. Here a fixed rotation is performed to move  $A[k]$  to the correct bit positions. The MUL module performs the core multiplication  $A[k] \cdot B[i, j]$  and later writes the result back.

An improved schedule is depicted in Figure 4b where Mul and Write perform simultaneously. To handle the diagonal computation, it takes  $5 + 2 + 1 + 2\lceil r/d \rceil$  cycle count where  $i = 0$ .  $\lceil r/d \rceil - 1$  iterations are required for the upper triangle computation. For the  $i = 1, 2, \dots, d - 1$ -th iteration, it consumes  $5 + 2 + 1 + \lceil r/d \rceil - 1 - i + 1$  cycles. Therefore the entire upper triangle computation costs  $(\lceil r/d \rceil^2 + 17\lceil r/d \rceil - 18)/2$  cycles. The same cycle count is needed for the lower triangle computation.

In general, the cycle count for the optimised generic polynomial multiplication is:

$$\lceil r/d \rceil^2 + 18\lceil r/d \rceil - 9$$

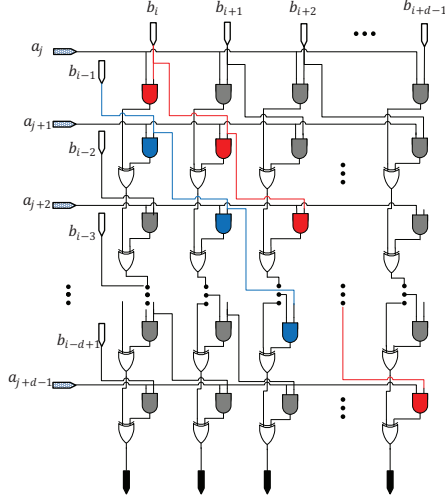


Fig. 5: Architectural overview of the core unit MUL in the generic multiplication

Table 3: Cycle count comparisons between unoptimized and optimized sparse polynomial multiplication modules.

Category		$d$	$r$	$ I  = w/2$	unoptimized version	optimized version
128-bit	BIKE-[1,2]	64	10163	71	180,624	90,880
	BIKE-[3]	64	11027	67	185,456	93,264
192-bit	BIKE-[1,2]	64	19853	103	512,528	257,088
	BIKE-[3]	64	21683	99	536,976	269,280
256-bit	BIKE-[1,2]	64	32749	137	1,122,304	562,248
	BIKE-[3]	64	36131	133	2,404,640	1,203,384

### 3.3 Sparse Polynomial Multiplication

In BIKE, a special form of multiplication called sparse polynomial multiplication, is frequently used. In sparse polynomial multiplication, one of the operands is a sparse polynomial whereas the other one is a dense polynomial. Such multiplications can be efficiently computed as follows: The sparse polynomial, *e.g.*,  $a(x)$  is first represented by an array of indices in  $I = \{i | a_i = 1\}$ . Then, the multiplication result can be obtained by extracting  $i \in I$  rows of  $\text{BT}_{mul}$  and then accumulating them, *i.e.*,  $\sum_{i \in I} x^i b(x)$  and the  $i$ -th row of the matrix  $\text{BT}_{mul}$  represents the coefficients of  $x^i b(x)$ . Formally, the coefficient vector of sparse polynomial multiplication can be calculated as:  $\sum_{i \in I} [b_{-i}, b_{-i+1}, \dots, b_{-i-1}]$ .

Figure 6a depicts the basic pipeline schedule where the total cycle count for one complete sparse polynomial multiplication is:

$$|I| \cdot \lceil r/d \rceil \cdot (10 + \lceil \log_2(d) \rceil)$$

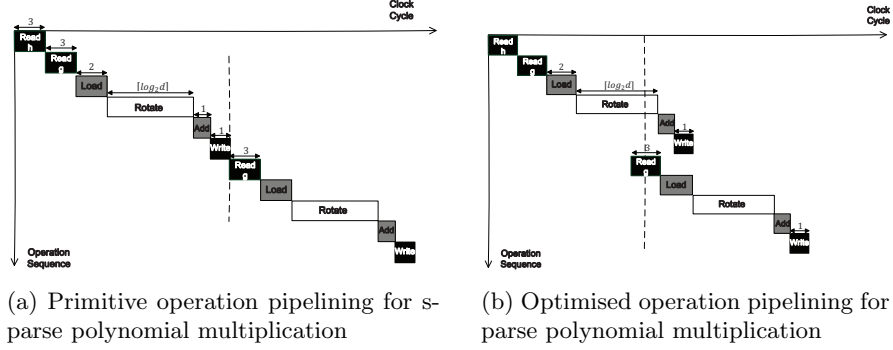


Fig. 6: Timing diagram used in sparse polynomial multiplication

The cycle count can be further improved if Read\_g is computed in parallel with Rotate while Load is computed in parallel with Add+Write. This optimized schedule for pipelining is presented in Figure 6b and the optimized cycle count is:

$$|I|(\lceil r/d \rceil \cdot (2 + \lceil \log_2(d) \rceil) + 8)$$

Table 3 present the cycle count of the two pipeline scheduling schemes. The optimized pipeline can improve the cycle count by about 50%.

### 3.4 Polynomial Inversion

**Theorem 2.** *Let  $a$  be an invertible polynomial in the quotient ring  $\mathbb{F}_2[x]/(x^r+1)$  where  $r$  is a prime, then the inverse of polynomial  $a$  can be computed as  $a^{-1} = (a^{2^{r-2}-1})^2$*

According to Theorem 1, we can compute the inverse of a polynomial over ring  $\mathbb{F}_2[x]/(x^r+1)$  by exponentiation. To efficiently compute the exponentiation of the polynomial, we propose a method which is described as follows. First, we define a function  $\beta_k(a) = a^{2^k-1}$ . It is easy to see that  $a^{-1} = (\beta_{r-2}(a))^2$ . Therefore, this recursive formula holds:  $\beta_{k+j}(a) = (\beta_k(a))^{2^j} \beta_j(a)$ .

With the above recursion formula, we can generate  $\beta_{r-2}(a)$  from  $\beta_1(a) = a$  through an addition chain in constant steps, which is known as Itoh-Tsujii Inversion algorithm (ITA), as shown in Algorithm 5. More importantly, the building blocks for ITA are polynomial squaring and multiplication which can be highly optimized in our design. Another common approach for polynomial inversion is through the Extended Euclidean algorithm (EEA). In [16], EEA with constant flow is proposed which can be exploited for secure polynomial inversions. However, the steps in the proposed algorithm are data-dependent and thus is not suitable for parallel designs on hardware. An illustrative example for computing the polynomial inversion used in BIKE-2 is shown in Table 9 in the Appendix.



<p><b>Input:</b> PRNG seed, polynomial length <math>r</math>, data width <math>d</math></p> <p><b>Output:</b> binary vector <math>\mathbf{f}</math> representing <math>f = f_0 + \dots + f_{r-1}x^{r-1} \in \mathbb{F}_2[x]/(x^r + 1)</math>, with odd weight <math> f  \approx r/2</math></p> <pre> 1 <math>wt \leftarrow 0</math> 2 <b>for</b> <math>i \leftarrow 0</math> <b>to</b> <math>\lceil r/d \rceil - 1</math> <b>do</b> 3   <math>\mathbf{f}[i] \leftarrow \text{truncate}_d(\text{SecureRand}(\text{seed}))</math> 4   <math>wt \leftarrow wt +  \mathbf{f}[i] </math> 5 <b>if</b> <math>wt</math> is even <b>then</b> 6   flip the first bit in <math>\mathbf{f}[i]</math> 7 <b>return</b> <math>\mathbf{f}</math> </pre>
---

**Algorithm 6:** Generation of a random polynomial with odd weight

<p><b>Input:</b> PRNG seed, polynomial length <math>r</math>, data width <math>d</math>, polynomial weight <math>wt = w/2</math></p> <p><b>Output:</b> integer vector <math>\hat{\mathbf{f}}</math> contains non-zero bit-positions (<math>\{i   f_i \neq 0\}</math>) to represent <math>f = f_0 + \dots + f_{r-1}x^{r-1} \in \mathbb{F}_2[x]/(x^r + 1)</math>, with odd weight <math> f  = wt</math></p> <pre> 1 <b>for</b> <math>i \leftarrow 0</math> <b>to</b> <math>wt - 1</math> <b>do</b> 2   <b>do</b> 3     <math>rand \leftarrow \text{truncate}_d(\text{SecureRand}(\text{seed}))</math> 4     <b>while</b> <math>rand \geq r</math> or <math>rand \in \hat{\mathbf{f}}</math> 5     <math>\hat{\mathbf{f}}[i] \leftarrow rand</math> 6 <b>return</b> <math>\hat{\mathbf{f}}</math> </pre>
---

**Algorithm 7:** Generation of a random sparse polynomial with given (odd) weight

if the Hamming weight of the polynomial is an even number; Algorithm 7 keeps generating new random numbers until a non-repeated number smaller than the system parameter  $r$  is generated. Nevertheless, in the following text we validate that these non-constant-time behaviors do not leak any secret information that can be exploited by an adversary: The optional step in Algorithm 6 flips the first bit-position of  $\mathbf{f}$  and the probabilistic distribution of this bit position does not change as long as the PRNG itself is unbiased (uniformly distributed). An adversary has no advantage in estimating the value of this specific bit even if he observes the timing difference. For Algorithm 7, the timing difference observed by an adversary is actually the total amount of time introduced by the re-generation of random numbers when an overflow ( $rand \geq r$ ) or a repetition ( $rand \in \hat{\mathbf{f}}$ ) occurs. An overflow does not leak any information about  $\hat{\mathbf{f}}$  as the information that the generated number is above  $r$  does not leak any information on  $\hat{\mathbf{f}}$ . The probability that the generated random number is smaller than  $r$  is  $Pr(rand < r) = r/2^{\lceil \log_2(r) \rceil}$ . To eliminate the possible timing leakage from the repetition, we introduce a method by changing the while-loop in step 4 of Algorithm 7 to **while**  $rand \geq r$ . In another word, we generate  $w_t$  random num-

Table 4: Success Rate for generating a random polynomial with odd weight using Algorithm 7

Category		no repetition	1 repetition	2 repetitions	success rate
128-bit	BIKE-[1,2]	0.7826	0.1926	0.0228	0.9981
	BIKE-[3]	0.8179	0.1649	0.0159	0.9989
192-bit	BIKE-[1,2]	0.7671	0.2040	0.0264	0.9976
	BIKE-[3]	0.7992	0.1796	0.0196	0.9985
256-bit	BIKE-[1,2]	0.7521	0.2148	0.0300	0.9970
	BIKE-[3]	0.7840	0.1911	0.0228	0.9981

Table 5: Cycle count for generating the sparse polynomial  $h_0/h_1$  in BIKE Key-Gen

Category		Total	$r$	$w_t$	$Pr(\text{rand} < r)$	$Pr(\text{Alg. 7 succeeds})$
128-bit	BIKE-[1,2]	1279	10163	71	0.62	0.9981
	BIKE-[3]	1062	11027	67	0.67	0.9989
192-bit	BIKE-[1,2]	2120	19853	103	0.60	0.9976
	BIKE-[3]	1847	21683	99	0.66	0.9985
256-bit	BIKE-[1,2]	2801	32749	137	0.99	0.9970
	BIKE-[3]	3350	36131	133	0.55	0.9981

bers each of which is smaller than  $r$  without considering whether they collide with each other or not. By doing this, no timing information is leaked on repetition but in this case, a few repetitions might occur which in turn reduces the Hamming weight of the generated sparse polynomial. However, a small loss of Hamming weight  $w$  is tolerable in BIKE: To reach  $\lambda$  bits of classical security,  $\lambda \approx w - \log_2 r$  for BIKE-1 and BIKE-2 and  $\lambda \approx w - \frac{1}{2} \log_2 r$  for BIKE-3, and 1 or 2 repetitions only decrease the security from  $2^\lambda$  to  $2^{\lambda-2}$ . More importantly, the probability that a single run of Algorithm 7 without considering collision succeeds if we tolerate one or two repetitions is:

$$Pr(\text{Alg. 7 succeeds}) = \frac{r(r-1) \cdots (r-w_t+1)}{r^{w_t}} + \frac{\binom{w_t}{2} r(r-1) \cdots (r-w_t+2)}{r^{w_t}} \quad (3)$$

$$+ \frac{[\binom{w_t}{3} + \binom{w_t}{2} \binom{w_t-2}{2}] r(r-1) \cdots (r-w_t+3)}{r^{w_t}} \quad (4)$$

The probability is very high (at least 0.997, as shown in Table 4):

Note that the design uses a simple PRNG based on linear congruence to enable deterministic generation of random numbers (*i.e.*, the function of *SecureRand*( $\cdot$ ) in Algorithm 6, 7). For real-world deployment, such PRNG must be replaced with a cryptographically secure random number generator, *e.g.*, [24, 9]. We require at most  $d$  random bits per  $T_{\text{PRNG}}$  clock cycles where  $T_{\text{PRNG}} = 13$  in our settings. The average clock cycles for generating a qualified rand number is  $T'_{\text{PRNG}} = T_{\text{PRNG}} / Pr(\text{rand} < r)$

Therefore, the total cycle count for generating a random polynomial with odd weight (Algorithm 6) is  $\lceil r/d \rceil \cdot T'_{\text{PRNG}} + 1$ .

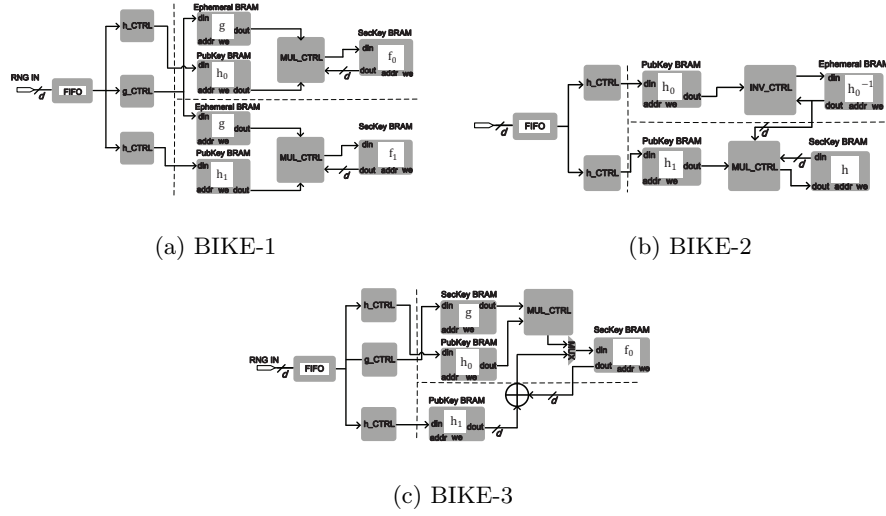


Fig. 8: Overview of the proposed BIKE architectures

We use the average case for Algorithm 7 to estimate the clock cycle count for generating a random sparse polynomial with given (odd) weight:

$$\left( w_t T'_{\text{PRNG}} + \frac{w_t(w_t + 1)}{2} + 5w_t \right) / \Pr(\text{Alg. 7 succeeds})$$

By using the FIFO-based architecture, random number generation and Hamming weight checking are parallelized since FIFO keeps buffering the random numbers regardless if the Hamming weight checking process is idle or not. This optimization brings the cycle count down to:

$$\left( T'^2_{\text{PRNG}} - 4T'_{\text{PRNG}} + \frac{T'_{\text{PRNG}} + w_t + 6}{2}(w_t - T'_{\text{PRNG}} + 5) \right) / \Pr(\text{Alg. 7 succeeds})$$

If a dual-port RAM is used, the above cycle count estimation can be further improved to:

$$\left( T''^2_{\text{PRNG}} - 4T''_{\text{PRNG}} + \frac{T''_{\text{PRNG}} + \lceil w_t/2 \rceil + 6}{2}(\lceil w_t/2 \rceil - T''_{\text{PRNG}} + 5) \right) / \Pr(\text{Alg. 7 succeeds})$$

where  $T''_{\text{PRNG}} = T_{\text{PRNG}} / \Pr^2(\text{rand} < r)$ . The detailed cycle counts for generating the sparse polynomial  $h_0/h_1$  in all BIKE variants are listed in Table 5.

## 4 Key Generator Architecture

Our key generator performs the computations in BIKE-1/2/3 as shown in Algorithm 1, Algorithm 2, and Algorithm 3. The top-level architectures are depicted



in Figure 8a, 8b, 8c respectively. BIKE-1 and BIKE-3 share similar architectures where the sparse polynomial multiplication module (SMUL\_CTRL in Section 3.3) is the core building block. The difference within the two architectures is that BIKE-1 requires two SMUL\_CTRL modules whereas BIKE-3 requires only one SMUL\_CTRL module and one additional addition unit. In our design, the two sparse polynomial multiplications in BIKE-1 are performed in parallel to improve the timing efficiency. Therefore, the total cycle count of BIKE-1 is close to that of BIKE-3. Among BIKE-1/2/3, the architecture of BIKE-3 is the most compact while the critical path is the shortest, this is mainly due to the simplicity of the architecture since only one SMUL\_CTRL is instantiated in BIKE-3. The modules `h_ctrl` and `g_ctrl` in BIKE-3 represents the control logic for generating the sparse polynomials  $h_0, h_1$  and the dense polynomial  $g$ , as discussed in Section 3.5.

The key generator architecture for BIKE-2 is significantly more expensive compared to BIKE-1 and BIKE-3. This is mainly due to the requirement of a polynomial inversion step in the key generation process, therefore a INV\_CTRL as described in Section 3.4 is needed. After the inversion operation, the inversed polynomial of  $h_0$  is obtained, which is represented as  $h_0^{-1}$ . Then, the sparse polynomial multiplication begins by triggering the SMUL\_CTRL module with polynomials  $h_0^{-1}$  and  $h_1$  as inputs. After the SMUL\_CTRL module finishes, the result is sent out as the output, which is the secret key  $h = h_0^{-1}h_1$ .

Similar optimizations as proposed to schedule pipelines as described in Section 3 are applied to the modules within the BIKE key generator as well. These optimizations improve the timing efficiency for the key generator.

## 5 Performance Evaluations

In this section, we present the hardware implementation results of the key generator of BIKE on FPGAs. All the results are obtained from the synthesis results on a Xilinx high-end FPGA device — Virtex XC7V585T and a low-end FPGA device — Spartan XC7S50 FPGA using the Xilinx Vivado v2018.1 synthesis tool. To the best of our knowledge, this work is the first that reports the performance results of the BIKE key generator on FPGA platforms.

As shown in Table 6, for our BIKE-1 key generator, when the design is synthesized on the Virtex-7 device, the synthesis tool reports a maximum frequency of 350 MHz. Our simulation result shows that it takes 95,506 cycles to generate one key pair for BIKE-1. Therefore, to generate a complete key pair for BIKE-1, only 0.273 *ms* are needed. When synthesized for a lower-end Spartan-7 device, our design is reported to be able to run at 160 MHz which leads to a key pair generation time of 0.597 *ms*. The area consumption of the key generator for BIKE-1 is very low: Only 612 slices and 544 slices are needed on Virtex-7 and Spartan-7 respectively. Compared to BIKE-1, the key generator for BIKE-3 is more compact since only one sparse polynomial multiplication module is needed instead of two. However, BIKE-3 takes slightly more cycles compared to BIKE-1 to generate a key pair due to the additional polynomial addition operation

Table 6: Performance results of BIKE key generators on a Xilinx Virtex-7 XC7V585T FPGA and a Xilinx Spartan-7 XC7S50 FPGA.

Aspect	BIKE-1		BIKE-2		BIKE-3	
	Virtex-7	Spartan-7	Virtex-7	Spartan-7	Virtex-7	Spartan-7
FFs	1055	993	2159	2098	955	911
LUTs	1970	1897	4445	3872	1482	1402
Slices	612	544	1483	1272	472	423
BRAM	7	7	10	10	4	4
Frequency(MHz)	350	160	320	150	360	200
Time/Op(ms)	0.273	0.597	6.719	14.334	0.273	0.492
Cycles: Compute $h_0$	1279		1279		1062	
Cycles: Compute $h_1$	1279		1279		1062	
Cycles: Compute $g$	2068		—		2250	
Cycles: Compute $h_0^{-1}$	—		2,056,683		—	
Cycles: Compute $f_0$	90,880		—		94,135	
Cycles: Compute $f_1$	90,880		—		—	
Cycles: Compute $h$	—		90,880		—	
Cycles: Total	95,506		2,150,121		98,509	

needed for computing the secret key  $f_0$  in BIKE-3. In terms of run time, the performance of the BIKE-3 key generator is slightly better than BIKE-1: The key pair generation take 0.273 *ms* and 0.492 *ms* respectively on Virtex-7 and Spartan-7 FPGAs.

For the BIKE-2 key generator, the synthesis tool reports frequencies as 320 MHz and 150 MHz on the Virtex-7 and Spartan-7 devices respectively. A full key generation in BIKE-2 takes 2,150,121 cycles which leads to run time of 6.719 ms and 14.334 ms respectively on Virtex-7 and Spartan-7 devices. As we can see from Table 6, BIKE-2 is around two orders of magnitude slower compared to BIKE-1 and BIKE-3. This performance gap between BIKE-2 and BIKE-1/3 is mainly due to the requirement of an expensive polynomial inversion operation in BIKE-2 while in BIKE-1/3 it is not needed. Due to the existence of the polynomial inversion module, the area utilization of BIKE-2 key generator is more than 2× bigger compared to BIKE-1/3 as well. Moreover, the memory overhead in BIKE-2 key generator is also larger than that of BIKE-1/3 since the polynomial inversion module requests to save a few ephemeral variables.

## 6 Related Work

In the following, we compare our work with previous designs. Hardware architectures for the classical McEliece/Niederreiter schemes based on binary Goppa codes have been extensively studied in the last decade [13, 36, 17, 20, 38, 39]. In 2018, Wang, Niederhagen and Szefer presented the fastest-to-date FPGA-based design for the Goppa code-based Niederreiter cryptosystem [39] which includes all the operations, i.e., key generation [38], encryption and decryption. As we can see from Table 8, with the same security level, cryptosystems based on binary Goppa codes require much more time, slices and memory to generate a key

Table 7: Performance comparison of our FPGA implementation with other code-based key generators.

Scheme	SL [bit]	Platform	$f$ [MHz]	Time/Op	Cycles	Slices/LUTs/FFs	BRAM
MDPC code:							
<b>Ours (BIKE-1)</b>			<b>165</b>	<b>0.578ms</b>	$9.55 \times 10^4$	<b>608/1907/1049</b>	<b>7</b>
<b>Ours (BIKE-2) 128</b>		Artix-7	<b>160</b>	<b>13.437ms</b>	$2.15 \times 10^6$	<b>1312/3874/2141</b>	<b>10</b>
<b>Ours (BIKE-3)</b>			<b>170</b>	<b>0.579ms</b>	$9.85 \times 10^4$	<b>453/1397/925</b>	<b>4</b>
Goppa code:							
[39]	256	Virtex Ultrascale+	225	3.98ms	$\approx 1.01 \times 10^{11}$	—/112845/—	375
[39]	103	Virtex-5	168	16ms	$\approx 2.72 \times 10^6$	8171/19257/20622	89
[7]	128	Artix-7	38.1	41.9ms	$\approx 1.59 \times 10^6$	—/25327/49383	168

pair. Such memory overhead is inevitable in Goppa code cryptosystems due to its large public key size which does not exist in cryptosystems based on quasi-cyclic codes. In addition, we re-implement our design and compare fairly with the FPGA implementation from the classic-McEliece NIST submission specification document published in 2019 [7], on the platform of Xilinx Artix-7. The results show that the timing and the area advantages of our work still preserve. Therefore, compared to binary Goppa code-based key generators, our design based on QC-MDPC codes is a much more lightweight design which is also much more efficient and has a much smaller memory overhead.

A few hardware designs have been proposed on MDPC code-based cryptosystems [21, 37, 22]. However, all of these designs only focus on the encryption/decryption operations in the cryptosystem. Therefore, a direct comparison of our work with other key generator architectures of MDPC code-based cryptosystems are not feasible.

To get a better comparison with other work on MDPC code-based cryptosystems, we also compared our work with the state-of-the-art software implementations of BIKE. Note that a fair comparison between our hardware design and other software implementations of BIKE is not feasible since the platforms are fully different. Comparison results are provided in Table 8. We first compare our design with the implementation which is included in the BIKE specification submitted to the NIST 2nd round PQC standardization process [1]. As we can see from Table 8, with the same security levels, for BIKE-1, our design is around  $7.7\times$  faster than the implementation in [1] in terms of cycle count. Moreover, the software implementation provided in [1] is not constant-time and therefore is vulnerable to timing side-channel attacks. An optimized software implementation for BIKE is reported in [12]. In this implementation, the core functionality in BIKE is written in assembly language, moreover, the PCLMULQDQ instruction extension is exploited to enable carry-less multiplication to speed up the polynomial multiplication computations in BIKE. The performance results of [12] is provided in Table 8. In terms of cycle count, for BIKE-1, the performance of our hardware design is comparable to [12] while an over  $2\times$  speedup is achieved in BIKE-2 by use of our dedicated hardware key generator.

Table 8: Performance comparison of our FPGA implementation with dedicate software implementations.

Scheme	SL [bit]	Implementation	Platform	Performance [in millions of cycles]
<b>BIKE-1</b>	128	Ours, constant-time	FPGA	0.095
	128	[1], non-constant-time	Intel Core-i5	$\approx 0.73$
	128	[12], non-constant-time	Intel Xeon-8124M	0.09
<b>BIKE-2</b>	128	Ours, constant-time	FPGA	2.15
	128	[1], non-constant-time	Intel Core-i5	$\approx 6.3$
	128	[12], non-constant-time	Intel Xeon-8124M	4.38
<b>BIKE-3</b>	128	Ours, constant-time	FPGA	0.098
	128	[1], non-constant-time	Intel Core-i5	$\approx 0.43$

## 7 Conclusions

This paper presented a constant-time hardware-based key generator for BIKE which is among the 2nd round candidates in the NIST PQC standardization process. Novel multiplication and squaring algorithms were proposed to accelerate the key generation with low logic overhead. Experimental results show that after a dedicate optimized pipeline scheduling for the proposed algorithms, our work outperforms other code-based hardware key generators in terms of timing performance, logic utilization and memory consumption. This work also outperforms the state-of-the-art software implementations of BIKE on powerful CPUs in terms of cycle count. The methods proposed in this paper are generic and applicable to other code-based schemes as well if the underlying code is quasi-cyclic.

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## Appendix

**Illustrative example for constant-time ITA used in BIKE.** We illustrate a concrete instance for computing the polynomial inversion used in BIKE-2 as shown in Table 9.

Table 9: An illustrative example for computing polynomial inverse  $a^{-1}$  in  $\mathbb{F}_2[x]/(x^r + 1)$  with  $r = 10163$  used in BIKE-2. This table explicitly demonstrates step by step a constant-time execution for inverse.

$i$	$u_i$	rule	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_i}(a) = a^{2^{u_i}-1}$
0	1	—	—	$\beta_{u_0}(a) = a^{2^1-1}$
1	2	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_1}(a) = a^{2^2-1}$
2	4	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_2}(a) = a^{2^4-1}$
3	8	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_3}(a) = a^{2^8-1}$
4	9	$u_{i-1} + u_0$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_4}(a) = a^{2^9-1}$
5	18	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_5}(a) = a^{2^{18}-1}$
6	19	$u_{i-1} + u_0$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_6}(a) = a^{2^{19}-1}$
7	38	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_7}(a) = a^{2^{38}-1}$
8	39	$u_{i-1} + u_0$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_8}(a) = a^{2^{39}-1}$
9	78	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_9}(a) = a^{2^{78}-1}$
10	79	$u_{i-1} + u_0$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{10}}(a) = a^{2^{79}-1}$
11	158	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{11}}(a) = a^{2^{158}-1}$
12	316	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{12}}(a) = a^{2^{316}-1}$
13	317	$u_{i-1} + u_0$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{13}}(a) = a^{2^{317}-1}$
14	634	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{14}}(a) = a^{2^{634}-1}$
15	635	$u_{i-1} + u_0$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{15}}(a) = a^{2^{635}-1}$
16	1270	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{16}}(a) = a^{2^{1270}-1}$
17	2540	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{17}}(a) = a^{2^{2540}-1}$
18	5080	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{18}}(a) = a^{2^{5080}-1}$
19	10160	$2u_{i-1}$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{19}}(a) = a^{2^{10160}-1}$
20	10161	$u_{i-1} + u_0$	$[\beta_{u_{i-1}}(a)]^{2^{u_{i-1}}} \cdot \beta_{u_{i-2}}(a)$	$\beta_{u_{20}}(a) = a^{2^{10161}-1}$

**Proof of Theorem 1.** We briefly prove Theorem 1 as follows: Consider the straightforward squaring operation for a random polynomial  $a(x) \in \mathcal{R}$ :

$$a^2(x) = (a_{r-1}x^{r-1} + a_{r-2}x^{r-2} + \cdots + a_1x + a_0)^2 \quad (5)$$

$$= a_{r-1}x^{2(r-1)} + a_{r-2}x^{2(r-2)} + \cdots + a_1x^2 + a_0 \quad (6)$$

$$= \widetilde{a_{r-1}}x^{r-1} + \widetilde{a_{r-2}}x^{r-2} + \cdots + \widetilde{a_1}x + \widetilde{a_0} \quad (7)$$



The computation of the coefficients  $\widetilde{a}_i$  can be realized by a matrix multiplication operation, which relies on the base transformation matrix BT, as shown follows:

$$a^2(x) = [a_0, a_1, \dots, a_{r-1}] \begin{bmatrix} x^0 \\ x^2 \\ \vdots \\ x^{2(r-2)} \\ x^{2(r-1)} \end{bmatrix} = [a_0, a_1, \dots, a_{r-1}] \cdot \text{BT}_{r \times r} \cdot \begin{bmatrix} x^0 \\ x^1 \\ \vdots \\ x^{r-2} \\ x^{r-1} \end{bmatrix}$$

where  $[\widetilde{a}_0, \widetilde{a}_1, \dots, \widetilde{a}_{r-1}] = [a_0, a_1, \dots, a_{r-1}] \cdot \text{BT}$  and BT is a  $r \times r$  permutation matrix defined as:

$$\text{BT} = \begin{bmatrix} \mathbf{1}_0 & 0 & \cdots & \cdots & \cdots \\ \cdots & \mathbf{1}_2 & 0 & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \mathbf{1}_{2r-4} & 0 & \vdots \\ \vdots & \vdots & \vdots & \mathbf{1}_{2r-2} & 0 \end{bmatrix}$$

$\mathbf{1}_i$  represents the  $(i \bmod r)$ -th (counting from zero) non-zero entry in the corresponding row of the matrix BT. More generally, we derive the base transformation matrix  $\text{BT}_n = \text{BT}^n$  for computing polynomial squaring continuously:  $a(x)^{2^n} = \widetilde{a_{r-1}}x^{r-1} + \widetilde{a_{r-2}}x^{r-2} + \cdots + \widetilde{a_1}x + \widetilde{a_0}$ . As we will see in Section 3.4, this is particularly useful in computing the inverse of a polynomial.

$$\text{BT}^n = \begin{bmatrix} \mathbf{1}_0 & 0 & \cdots & \cdots & \cdots \\ \cdots & \mathbf{1}_{2^n} & 0 & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \mathbf{1}_{(r-2)2^n} & 0 & \vdots \\ \vdots & \vdots & \vdots & \mathbf{1}_{(r-1)2^n} & 0 \end{bmatrix}$$

In order to compute the coefficient vector  $[\widetilde{a}_0, \widetilde{a}_1, \dots, \widetilde{a_{r-1}}] = [a_0, a_1, \dots, a_{r-1}] \cdot \text{BT}^n$ ,  $\text{BT}^n$  must be represented in column view format, *i.e.*, the row number of the non-zero entry for every column of  $\text{BT}^n$ . In this form, the squaring of  $a(x)$  is essentially the substitutions of the coefficients of  $a(x)$ :

$$\text{BT}^n = \begin{bmatrix} \mathbf{1}_0 & \vdots & \vdots & \vdots & \vdots \\ \vdots & \mathbf{1}_{2^{-n}} & \vdots & \vdots & \vdots \\ \vdots & \vdots & \mathbf{1}_{(r-2)2^{-n}} & \vdots & \vdots \\ \vdots & \vdots & \vdots & \mathbf{1}_{(r-1)2^{-n}} & \vdots \end{bmatrix}$$

**Remarks on generic multiplication.** We describe the proposed generic multiplication algorithm (Algorithm 4) in more details here. Similar to the proposed

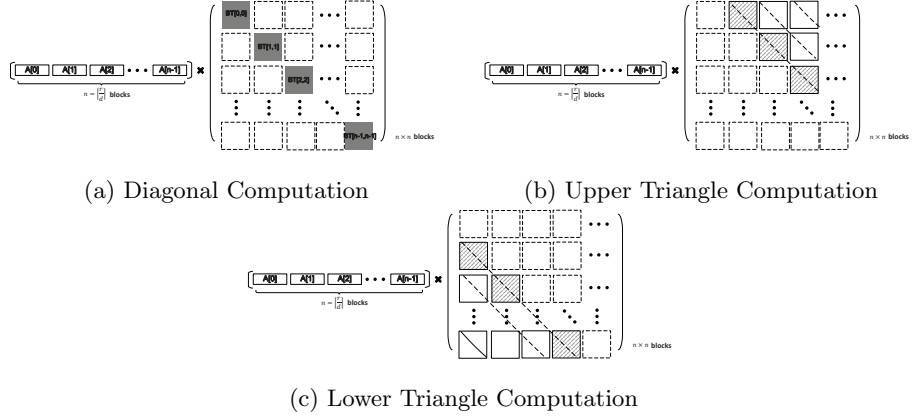


Fig. 9: Illustration for the proposed generic multiplication algorithm

squaring algorithm, another base transformation matrix  $\text{BT}_{mul}$  is used to compute the coefficients  $\tilde{c}_i$ , shown as follows:

$$a(x)b(x) = [\tilde{c}_0, \tilde{c}_1, \dots, \tilde{c}_{r-1}] \begin{bmatrix} x^0 \\ x^1 \\ \vdots \\ x^{r-2} \\ x^{r-1} \end{bmatrix} = [a_0, a_1, \dots, a_{r-1}] \cdot \text{BT}_{mul, r \times r} \cdot \begin{bmatrix} x^0 \\ x^1 \\ \vdots \\ x^{r-2} \\ x^{r-1} \end{bmatrix}$$

$\text{BT}_{mul}$  is a  $r \times r$  matrix where each column/row is a cyclic form of the vector  $[b_{r-1}, b_{r-2}, \dots, b_1, b_0]$ :

$$\text{BT}_{mul} = \begin{bmatrix} b_0 & b_1 & \dots & b_{d-1} & \dots & b_{r-1} \\ b_{r-1} & b_0 & \dots & b_{d-2} & \dots & b_{r-2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b_2 & b_3 & \dots & b_{d+1} & \dots & b_1 \\ b_1 & b_2 & \dots & b_d & \dots & b_0 \end{bmatrix}$$

Storing the full  $\text{BT}_{mul}$  matrix is redundant since the blocks along each diagonal are identical (for example,  $\text{BT}_{mul}[0 : d-1, 0 : d-1] = \text{BT}_{mul}[d : 2d-1, d : 2d-1] = \dots$ ). This way,  $\text{BT}_{mul}$  is split into three parts: the central diagonal, the upper triangle, and the lower triangle. Figure 9a, 9b, and 9c illustrate how to compute these parts. By eliminating such redundancy, the communication overhead for loading  $\text{BT}_{mul}$  is minimized which enables a fast pipeline scheduling in the generic polynomial multiplication module.