Synthesis of Flexible Accelerators for Early Adoption of Ring-LWE Post-quantum Cryptography

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The advent of the quantum computer makes current public-key infrastructure insecure. Cryptography community is addressing this problem by designing, efficiently implementing, and evaluating novel public-key algorithms capable of withstanding quantum computational power. Governmental agencies, such as NIST, are promoting standardization of quantum-resistant algorithms that is expected to run for 7 years. Several modern applications must maintain permanent data secrecy; therefore, they ultimately require the use of quantum-resistant algorithms. Because algorithms are still under scrutiny for eventual standardization, the deployment of the hardware implementation of quantum-resistant algorithms is still in early stages.

In this article, we propose a methodology to design programmable hardware accelerators for lattice-based algorithms, and we use the proposed methodology to implement flexible and energy efficient post-quantum cache-based accelerators for *NewHope*, *Kyber*, *Dilithium*, Key Consensus from Lattice (*KCL*), and *REMBLEM* submissions to the NIST standardization contest.

To the best of our knowledge, we propose the first efficient domain-specific, programmable cache-based accelerators for lattice-based algorithms. We design a single accelerator for a common kernel among various schemes with different kernel sizes, i.e., loop count, and data types. This is in contrast to the traditional approach of designing one special purpose accelerators for each scheme.

We validate our methodology by integrating our accelerators into an HLS-based SoC infrastructure based on the X86 processor and evaluate overall performance. Our experiments demonstrate the suitability of the approach and allow us to collect insightful information about the performance bottlenecks and the energy efficiency of the explored algorithms. Our results provide guidelines for hardware designers, highlighting the optimization points to address for achieving the highest energy minimization and performance increase. At the same time, our proposed design allows us to specify and execute new variants of lattice-based schemes with superior energy efficiency compared to the main application processor without changing the hardware acceleration platform. For example, we manage to reduce the energy consumption up to 2.1× and energy-delay product (EDP) up to 5.2× and improve the speedup up to 2.5×.

This work was supported in part with a gift from Qualcomm Technology Inc., Swiss National Science Foundation project No P1TIP2_181305 and European Union Horizon 2020 research and innovation programme under SAFEcrypto project (grant agreement No 644729). Additionally, Subhadeep Banik was supported by Swiss National Science Foundation project No PZ00P2_179921.

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1539-9087/2020/03-ART11 \$15.00

<https://doi.org/10.1145/3378164>

CCS Concepts: • **Security and privacy** → **Public key (asymmetric) techniques**; *Hardware-based security protocols*;

Additional Key Words and Phrases: Public key cryptography, post-quantum cryptography lattice-based cryptography, ideal lattices, domain specific acceleration, cache architecture

ACM Reference format:

Hamid Nejatollahi, Felipe Valencia, Subhadeep Banik, Francesco Regazzoni, Rosario Cammarota, and Nikil Dutt. 2020. Synthesis of Flexible Accelerators for Early Adoption of Ring-LWE Post-quantum Cryptography. *ACM Trans. Embed. Comput. Syst.* 19, 2, Article 11 (March 2020), 17 pages.
<https://doi.org/10.1145/3378164>

1 INTRODUCTION

A worldwide research effort is currently pursuing a scalable quantum computer. Quantum computers, as envisioned by Richard Feynman [14], use quantum mechanics to carry out computation that can reach an exponential speedup in several applications, such as quantum chemistry [29]. Exponential speed up can also be reached in other problems, such as the search for the period of a function. As demonstrated by Peter Shor [34], it would allow us to factorize integers in polynomial time and ultimately render the public key infrastructure insecure. Post-quantum cryptography is a vibrant area of research devoted to studying alternative public-key algorithms, executed on classical computers but capable of withstanding quantum computational power. The effort of governmental agencies in conducting the standardization of these novel algorithms endorses the urgency of the threat. The most relevant standardization effort is that of NIST, which started in 2017 with the submissions of potential candidates and continues with the evaluation of the candidates for the next 6 to 7 years, until the selection of the new standards.

In the long run, achieving resistance against quantum attacks is vital, because there will be devices based on classical architectures even after the invention of quantum computers. Quantum resistance is fundamental for an application that requires the “long-term security,” namely that the data should be kept secret for an extended time-period (even much longer than the one envisioned for building a quantum computer). For such applications, it is of utmost importance to have an immediate deployment of quantum-resistant algorithms.

The experimentation of quantum-resistant algorithms is already ongoing in software platforms (for instance, Google Chrome started the tests of NewHope). However, for the complete adoption of post-quantum algorithms, it is necessary to meet the requirements of specific applications that necessarily need to rely on dedicated hardware. The early adoption of quantum-resistant hardware is challenging, because in this period of transition, during which candidates are still under the evaluation, a post-quantum standard is yet to be decided and also the parameters of the candidates themselves can change; subsequently, it is troublesome to commit to a specific algorithm and a specific set of parameters, knowing that they could be soon outdated [27].

The situation would change if the accelerators would be able to meet two requirements: (1) reach the required performance and (2) be flexible, thus “robust” to change in parameters and algorithms (providing the so-called crypto-agility). To meet these goals, we propose to accelerate, instead of a complete algorithm, only several portions of the software routines, called micro-kernels. Compared to a whole dedicated accelerator, a micro-kernel accelerator does not reach the same level of performance, because the main processor executes parts of the computation. Subsequently, hardware acceleration based on micro-kernels is more flexible compared to the classical counterparts. We provide two dimensions of flexibility by designing a single 32-bit accelerator for a kernel that is used by various schemes with different data types, e.g., `uint32_t`, `uint16_t`, `int32_t`, `int16_t`. The

size of the same kernel can be different over different schemes, e.g., ranging from 128 to 512 loop iterations. We design a single accelerator by applying different compiler and architectural optimizations that can execute the same kernel for all the schemes.

To enable early adoption of quantum-resistant algorithms, in this article, we use a design space exploration framework, adopted by us to post-quantum cryptography, to explore the design space of micro-kernel-based acceleration of lattice-based cryptography (LBC) algorithms and to implement them. We focus on domain-specific programmable hardware accelerators, because they are the most suitable, at this stage, to adopt post-quantum algorithms in hardware. We concentrate on lattice-based algorithms, the most promising family of quantum-resistant algorithms thanks to their versatility and their excellent performance. Around half of the submission to the first round of the NIST PQC Standardization Process belong to this family. After a year of evaluation, 26 of the candidates are chosen for the second round; twelve candidates belong to lattices, and the remaining 14 candidates belong to code-based, hash-based, supersingular elliptic curve isogeny, and multivariate cryptography [27]. Finally, we concentrate on energy and performance as the main figure of merit, since these would be the most relevant parameters for IoT and battery-operated devices, as well as for servers and cloud accelerators [23].

The rest of the article is organized as follows: Section 2 provides the background for LBC primitives and summarizes the state of the art in design space exploration for cryptography and in accelerating LBC; Section 3 and Section 4 describe the design flow steps and the profiling results for the selected algorithms. Section 5 discusses the DSE results and elaborates on the design point selection.

2 BACKGROUND AND RELATED WORKS

A lattice $L \subset \mathbb{R}^n$ is the set of all integer linear combinations of basis vectors $\mathbf{b}_1, \dots, \mathbf{b}_n \in \mathbb{R}^n$. i.e., $L = \left\{ \sum a_i \mathbf{b}_i : a_i \in \mathbb{Z} \right\}$. In particular, L is a subgroup of $\mathbb{R}^n$ that is isomorphic to $\mathbb{Z}^n$. The cryptography based on lattices exploits the hardness of two problems: Short Integer Solution (SIS) and Learning With Errors (LWE). Cryptosystems based on the LWE problem, the most used one, have their foundation in the difficulty of finding the secret key sk , given (A, pk) , where $pk = A * sk + e \bmod q$, with pk being the public key, e an error vector with Gaussian distribution, and A a matrix of constants in $\mathbb{Z}_q^{r \times n}$ chosen randomly from a uniform distribution. In general, the parameters n , r , and q are integers such that $n > 1$, $r > n$, and $q \geq 2$, but for some efficient implementations these numbers are constrained to a limited set of values. For more detailed information about the parameters, we refer to the survey done by Oded Regev [31].

LWE, however, requires large keys that could be impractical; for instance, public and secret key size of Frodo [22], LWE-based KEM, at NIST security level 1 are 9 KB and 19.8 KB, respectively. To overcome this limitation, Lyubashevsky et al. [21] introduced Ring-LWE (RLWE), a derivation of LWE where A is implicitly defined as a vector a in the ring $\mathcal{R} \equiv \mathbb{Z}_q[x]/\langle x^n + 1 \rangle$. These lattices are called Ideal lattices, while other lattices are called Standard lattices. At the same security level as Frodo, NewHope [30], a RLWE-based KEM, provides 10× smaller public and secret keys. Since implementing a polynomial multiplication requires a notable amount of computational resources, it is implemented using the so-called Number Theoretic Transform (NTT), which is a Fast Fourier Transform implemented over a ring. In the rest of this section, we introduce a detailed definition of RLWE and number-theoretic transform.

Notations

In an RLWE encryption scheme, operations are performed on polynomials. We denote polynomials in the time domain by a lowercase letter, e.g., x , and whenever we want to access one coefficient of the polynomial, we denote $x(i)$. Polynomials in the frequency domain are denoted by uppercase

ALGORITHM 1: RLWE Key generation

Require: Access to a global constant $\mathbf{a}$ that was uniformly chosen from R_q

- 1: **function:** $RLWE_{keyGen}(a)$
- 2: $r_1, r_2 \leftarrow D_{\mathbb{Z}^n, \sigma}$
- 3: $p_k \leftarrow r_1 - ar_2$
- 4: $s_k \leftarrow r_2$
- 5: **return** (pk, sk)
- 6: **end function:**

ALGORITHM 2: RLWE Encryption

Require: Access to a global constant $\mathbf{a}$ that was uniformly chosen from R_q and to a message $\mu \in \{0, 1\}^n$

- 1: **function:** $RLWE_{enc}(pk, \mu)$
- 2: $e_1, e_2, e_3 \leftarrow D_{\mathbb{Z}^n, \sigma}$
- 3: $\tilde{m} \leftarrow Encode(\mu)$
- 4: $c_1 \leftarrow ae_1 + e_2$
- 5: $c_2 \leftarrow pke_1 + e_3 + \tilde{m}$
- 6: **return** (c_1, c_2)
- 7: **end function:**

ALGORITHM 3: RLWE Decryption

- 1: **function:** $RLWE_{dec}(c_1, c_2, sk)$
- 2: $\mu' \leftarrow Decode(c_1 \cdot sk + c_2)$
- 3: **return** μ'
- 4: **end function:**

letters. Multiplication of integers is described by $\cdot$ while we use $*$ for multiplication of polynomials. We omit $\cdot$ and $*$ where it is clear from the context.

2.1 Ring-LWE Encryption Scheme

The cryptosystems analyzed in this article are mostly based on a ring-variant of the LWE problem [21, 31]. The hard problem to be solved on the ring $\mathcal{R} = \mathbb{Z}_q[x]/\langle x^n + 1 \rangle$, which defines as deciding whether the samples $(a_1, t_1), \dots, (a_m, t_m) \in \mathcal{R} \times \mathcal{R}$ are chosen uniformly random or whether each $t_i = a_i s + e_i$, being $s, e_1, \dots, e_m$ small coefficients from the (one-dimensional) discrete Gaussian distribution $\mathcal{D}_\sigma$ [21]. The distribution $\mathcal{D}_\sigma$ is defined such that a value $x \in \mathbb{Z}$ is sampled from $\mathcal{D}_\sigma$ with the probability $\rho_\sigma(x)/\rho_\sigma(\mathbb{Z})$, where $\rho_\sigma(x) = \exp(-\frac{x^2}{2\sigma^2})$ and $\rho_\sigma(\mathbb{Z}) = \sum_{k=-\infty}^{\infty} \rho_\sigma(k)$.

The algorithms for key generation, encryption, and decryption are presented in Algorithm 1, Algorithm 2, and Algorithm 3, respectively. The key generation uses a constant vector a for obtaining the public and secret key (pk, sk) . The encryption procedure takes a binary string μ and releases the ciphers (c_1, c_2) , which are used in the decryption to recover the message μ' . The vectors r_1, r_2, e_1, e_2, e_3 are error vectors sampled from a Gaussian distribution.

The Number-Theoretic Transform (NTT) transforms a finite field polynomial from the time to the frequency domain. Inverse Number-Theoretic Transform (NTT^{-1}) transforms back the polynomial to the time domain. Polynomial multiplication in the frequency domain has linear complexity instead of quadratic complexity. As the transformation itself has quasi-linear complexity, the overall effort for polynomial multiplication drops from $O(n^2)$ to $O(n \cdot \log n)$. The efficient computation of the NTT involves the coefficient ring to contain primitive roots of unity. Formally, a primitive root of unity is defined as follows.

Definition 2.1 (Primitive Root of Unity). Let $\mathcal{R}$ be a ring, $n \in \mathbb{N}_{\geq 1}$, and $\omega \in \mathcal{R}$. The value ω is an n th root of unity if $\omega^n = 1$. The value ω is a primitive n th root of unity (or root of unity of order n) if it is an n th root of unity, $\omega^n \in \mathcal{R}$ is a unity in $\mathcal{R}$, and $\omega^{n/t} - 1$ is not a zero divisor for any prime divisor t of n .

For a given primitive n th root of unity ω in $\mathbb{Z}_q$, the NTT of a vector $a = (a(n-1), \dots, a(0))$ is the vector $A = (A(n-1), \dots, A(0))$ and it is computed as $A(i) = \sum_{j=0}^{n-1} a(j)\omega^{ij} \bmod q$, $i = 0, 1, \dots, n-1$. The inverse transformation is calculated as $a(i) = n^{-1} \sum_{j=0}^{n-1} A(j)\omega^{-ij} \bmod q$, $i = 0, 1, \dots, n-1$.

The idea is to transform two polynomials $a = a(n-1) \cdot x^{n-1} + \dots + a(0)$ and $b = b(n-1) \cdot x^{n-1} + \dots + b(0)$ into their NTT representations $A = A(n-1) \cdot x^{n-1} + \dots + A(0)$ and $B = B(n-1) \cdot x^{n-1} + \dots + B(0)$ and to compute the coefficient-wise multiplication as $C = \sum_{i=0}^{n-1} A(i) \cdot B(i) \cdot x^i$. The result $c = a * b$ is obtained after the computation of the inverse number theoretic transform (NTT^{-1}) to C . For $q = 1 \bmod 2n$, the way the result has to be interpreted depends on the input. Two common algorithms of performing number theoretic transform are Cooley-Tukey (CT) [10], which produces the result in the bit-reverse order by receiving the input in the correct order, and Gentleman-Sande (GS) [16], which receives the input in the reverse order and produces the output in the correct order. We refer to Gentleman-Sande and Cooley-Tukey algorithms as NTT_CT and NTT_GS, respectively, in the rest of this article. Employing NTT_GS to compute both NTT and NTT^{-1} involves in bit-reverse calculation (NewHope); however, bit-reverse step can be skipped by using NTT_CT for NTT and NTT_GS for NTT^{-1} (Kyber and Dilithium).

Keccak is a family of cryptographic primitives primarily as a candidate for the NIST SHA-3 competition [8]. The main transformation in the family is the Keccak-f[1600] permutation, which is used in the sponge mode in the specification for the SHA-3 hash function. The hash function operates on a state of 1,600 bits and is designed for easy implementation in both software and hardware. The state can be considered to be a $5 \times 5 \times 64$ array of bits. Let $a[i][j][k]$ be bit $(5i + j) \times w + k$ of the input, using a little-endian bit numbering convention and row-major indexing. Index arithmetic is performed modulo 5 for the first two dimensions and modulo w for the third. A set of 64 bits with the same x, y coordinates is called a lane. The basic block permutation function consists of 24 rounds of five steps (Figure 7).

- θ : In this step, we compute the parity of each of the 320 five bit columns and add it two nearby columns. Functionally it can be described as $a[x][y][z] \leftarrow a[x][y][z] + \sum_{y'=0}^4 a[x][y'][z] + \sum_{y'=0}^4 a[x+1][y][z-1]$
- ρ : In this step we rotate each of the lanes by a fixed number of bits. The transformation is given by $a[x][y][z] \leftarrow a[x][y][z - (t+1)(t+2)/2]$ where $t = -1$, if $x = y = 0$ and otherwise $t \in [0, 24]$ satisfying $\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 3 & 2 \\ 1 & 0 \end{pmatrix}^t \begin{pmatrix} 0 \\ 1 \end{pmatrix}$
- π : The mapping π is a transposition of the lanes. It is defined as $a[x][y][z] \leftarrow a[x'][y'][z]$, with $x = y'$, $y = 2x' + 3y'$
- χ : This is the only non-linear step in the round function given by $a[x][y][z] \leftarrow a[x][y][z] + (a[x+1][y][z] + 1)a[x+2][y][z]$
- ι : This is the round constant addition step. A round constant is added only to the lane with co-ordinates $(0,0)$.

The energy cost of implementation is crucial for constraint devices and servers; energy consumption of classical cryptography has been evaluated by many authors [3, 11, 36, 37]. However, for lattice-based cryptography, previous works focused mainly on limiting the area and improving the performance [5, 17]. However, energy has been left mostly unexplored, except for FPGA implementation [25], ASIC implementation [6], and simulation-based [26] accelerator for NTT,

Fig. 1. Design flow of the accelerator generation. After choosing the domain and algorithms, we identify the common kernels by profiling the applications using `perf` Linux and `gem5` [9]. The next steps are the code manipulation, DSE generation (using `gem5-Aladdin`), and sensitivity analysis. Afterward, we select the best design point for each kernel by considering the target platform. We evaluate the accelerator's power and performance within the SoC inside the `gem5-Aladdin` [33] simulator. The last step is to verify the algorithm using the original software implementation.

where none of them are cache-based accelerators. The early results of this work were presented in Reference [24].

3 DESIGN FLOW STEPS

In this section, we detail the three main steps that compose our design space exploration flow: profiling, early exploration, and evaluation within the target architecture. Figure 1 illustrates the design flow steps to generate flexible accelerators for any domain or set of algorithms. The first step is the profiling of the implementations of the target lattice-based schemes. This process is needed to identify the bottlenecks and the kernel to be accelerated. Profiling is executed by running the algorithm on a host arbitrary machine, e.g., X86-based system, and verify it using a microarchitectural simulator such as `gem5` [9]. In the former case, profiling results correspond to collecting performance counters from the execution. In the latter case, profiling means collecting simulation statistics. In either case, the same hot-spots in the protocol are identified. We profile the server and the client portion of the protocol separately to accommodate the specific needs of each endpoint. The identified hot-spot functions are candidates for acceleration and are input in our design exploration flow.

In the second step, we used `gem5-Aladdin` [33] to perform the design space exploration of the candidate functions. `gem5-Aladdin` is a fast design exploration framework that allows making decisions on the tradeoff between performance, power, and area of the identified design points with high accuracy, even avoiding the explicit HLD synthesis step. For standard linear algebra kernels, pre-RTL performance area and power estimation fall within a threshold of 10% compared

to the actual HLD synthesis. The results of the DSE are stored in an elastic search service, which we develop to keep track of the design points and to compare them in terms of area, power, performance, and complexity. The DSE itself consists on the extraction of instruction-level parallelism in each candidate function and the mapping of such parallelism on a parameterizable set of finite constraints in the hardware, e.g., number of vector lanes, vector lane pipeline depth, ports to memory, and communication to memory (with cache or via streaming) [33]. The introduction of system-level requirements allows us to query the elastic search service and to prune down the set of possible designs further. We use three-dimensional (latency, power, and area) Pareto-optimal fronts to eliminate non-optimal points. The design points that are not pruned will be evaluated in the whole system on the chip.

In the third step, we exploit the integration between gem5 and Aladdin [33] to evaluate the accelerator within the whole SoC. We used this approach to avoid Transaction Level Simulation, emulation, or full-system HLD synthesis. The memory communication and the host processor computation aspects are modeled in a pre-RTL environment. Thanks to the accuracy guaranteed by gem5 and Aladdin [33], this last step allows us to identify a restricted set of design points that quickly reach our design goals.

In this work, we accelerate the execution of lattice-based cryptography algorithms using co-processors with the small instruction set. Based on Figure 7, these accelerators are loosely coupled with the main processor in a System on Chip (SoC). Each accelerator has its private caches and operates in slave mode attached to the network on chip.

The accelerators are kernel-level accelerators, where the kernel to accelerate is the bottleneck functions that are common across different families of lattice-based cryptography schemes. For instance, any call to NTT_GS is transferred to the accelerator; if the size of the NTT_GS, i.e., polynomial degree, which determines the security strength, is bigger than the accelerator, we orchestrate the data stream via the cache hierarchy. In other words, the accelerator is a pipelined implementation of the kernel that arbitrary size of a call to the kernel can be offloaded to it.

The choice of this type of accelerator allows us to maintain high flexibility while at the same time, improving performance. This strategy ensures crypto-agility, which is fundamental for the early adoption of post-quantum algorithms. Additionally, it allows us to accelerate several lattice-based cryptography schemes with a small set of co-processors. Both advantages could not have been achieved using designs customized on each scheme.

4 ALGORITHMS PROFILING

We considered four key encapsulation mechanisms (NewHope, Kyber, R.EMBLEM, and KCL) and a digital signature algorithm (Dilithium). A KEM is a technique to encapsulate a symmetric key using an asymmetric cryptographic algorithm [28]. A digital signature is a scheme that guarantees the integrity and authenticity of a message. In the rest of the section, we discuss their profiling results.

4.1 NewHope

NewHope cryptosystem is a suite of two KEMs based on NewHope-Simple [2] that bases its security on the hardness of RLWE problem. NewHope is the transformation of a Public Key Encryption (PKE) scheme into a KEM using the Targhi and Unruh transforms [35] that implies the use of hash functions, which in the case of NewHope is Shake256 [13]. Also, NTT and binomial samplers are employed to improve the performance of the algorithm. The current submission of NewHope to NIST competition presents two parameter sets, NewHope512cpa/cca and NewHope1024cpa/cca, with security levels of 101 bits and 233 bits, depending on the length of ring polynomials [30].

Fig. 2. Profiling results for NewHope: Client-Server. Profiling results are based on the user-level CPU cycles.

Fig. 3. Profiling results for Kyber: Client-Server. Profiling results are based on the user-level CPU cycles.

Fig. 4. Profiling results for Dilithium: Sign-Verify. Profiling results are based on the user-level CPU cycles.

Figure 2 presents the profile of NewHope1024cpa, referred to as NewHope in the rest of the article, in the client and server-side. NewHope employs NTT_GS for both forward and inverse NTT.

4.2 Kyber

Kyber is a KEM based on the LWE problem in module lattices [19] that is built using the Fujisaki-Okamoto transform [15]. Kyber uses NTT_CT and NTT_GS to compute forward and reverse NTT, respectively. Kyber is presented in three versions: Kyber512, Kyber768, and Kyber1024 with the quantum hardness 102, 161, and 241 bits, respectively [4]. Due to the similarity, we only analyze Kyber768 in this article. The profile of Kyber768, referred to as Kyber in the rest of the article, is shown in Figure 3.

4.3 Dilithium

Dilithium is a signature algorithm based on the “Fiat-Shamir with Aborts” approach [20] that is designed to be easy to implement securely [12]. Its main characteristics are small signature and keys, conservative parameters, and modular structure. The most relevant operations in Dilithium are eXtendable-Output Functions (XOF) and polynomial multiplication in a ring. SHAKE128 and Shake256 are used as XOF. Similarly to Kyber, Dilithium uses NTT_CT and NTT_GS to compute forward and reverse NTT, respectively. The profile of Dilithium for signature and verification processes are reported in Figure 4.

Fig. 5. Profile R.EMBLEM: Client-Server.

Fig. 6. Profile AKCN_MLWE: Client - Server.

4.4 R.EMBLEM

R.EMBLEM (and its standard lattice variant EMBLEM) is an error-blocked multi-bit RLWE-based (LWE-based) key encapsulation mechanism [32]. Small keys size is achieved by separating the message from error and attach the error-blocking bit to each message block. Sampling the secret term is performed uniformly at random in $[-B, B]$. Similarly to Kyber and Dilithium, R.EMBLEM uses NTT_CT and NTT_GS to compute forward and reverse NTT, respectively.

4.5 KCL (Key Consensus from Lattice)

Zhao et al. [38] propose a generic construction of the authenticated key exchange, public-key encryption, and key encapsulation mechanism, including asymmetric key consensus (AKCN) and optimal asymmetric key consensus (OKCN). Proposed schemes are based on LWE and its variants over ideal and module lattices with different mathematical structures. Authors propose single error correction (SEC) code to correct at least one-bit error; using the SEC, at the same security level and error rate, OKCN/AKCN-RLWE-based KEX schemes generate 765-bit shared a key with less bandwidth than NewHope (256-bit shared key). Due to the similarity and to avoid the repetition, we provide the results for AKCN-MLWE. AKCN-MLWE uses NTT_CT to compute the forward and reverse NTT.

Table 1 shows summarized the size of the common kernels and the data types that they perform the computations. Keccak performs 25 iterations on unsigned 64-bit data. However, for NTT_GS and NTT_CT data types are different over different schemes. One 32-bit accelerator for NTT_GS and another 32-bit for NTT_CT are designed that can support calculation of forward and inverse number theoretic transform over the analyzed schemes with various data bitwidth, which is introduced in this work for the first time.

5 EVALUATION

The first step is to identify compute-intensive kernels, Section 4, and then search the space of the design and select the desired design points and evaluate them within an SoC. We use the original software implementation of the accelerated algorithms as a baseline for our evaluation. These implementations are the references for generating the KAT files, which enables us to use them

Table 1. Size of Loop and Data Types for NTT_GS and NTT_CT over Different Schemes

Scheme	Loop Iterations	Data type	
		Coefficients	Twiddle factor
NewHope512cpa/cca	256	uint16_t	uint16_t
NewHope1024cpa/cca	512	uint16_t	uint16_t
Kyber	128	uint16_t	uint16_t
Dilithium	128	uint32_t	uint32_t
R.EMBLEM	512	int32_t	int32_t
AKCN_MLWE	128	int32_t	int16_t

It should be mentioned that the data type for Keccak perform operations over uint64_t for all the schemes.

Fig. 7. Architectural template for generated accelerators for Keccak, (NTT_CT), and (NTT_GS) kernels. Sweepable micro-architectural and compiler parameters are shown in the first column of the table; the next column is the searched spaced in this work.

for verifying the accelerator's functionality. To apply our methodology in algorithms, the usage of KAT files can be integrated into the tool flow.

Figure 7 shows the architectural template of the designed accelerators, which are composed of a set of lanes that implement the primitives of the kernel, a Translation Lookaside Buffer (TLB), one level of cache, and the respective controller. Our tool allows analyzing the accelerators without digging into the details of the hardware implementations concentrating on the accelerator functionality.

Based on the profiling results (Figures 2–6), the top three common kernels that consume most of the cycles are NTT_CT, NTT_GS, and Keccak.

Keccak permutation consists of bitwise arithmetic operations, and each datapath lane of the accelerator has basic components to compute the F[1600] permutation function. The designed accelerator for Keccak can be used in any cryptographic scheme to hash a message and generate pseudo-random numbers. NTT_CT and NTT_GS accelerators are two programmable accelerators that can be employed inside any scheme with arbitrary security parameters to perform the number theoretic transform. Each datapath lane in NTT_CT and NTT_GS accelerators (Figure 7) executes the butterfly operation. To perform NTT and NTT^{-1} in NewHope, NTT_GS is used. However, AKCN_MLWE uses NTT_CT to compute both NTT and NTT^{-1} . Kyber, Dilithium, and R.EMBLEM perform NTT with NTT_CT and NTT^{-1} with NTT_GS.

Fig. 8. The sensitivity of the accelerators' performance and power to the *number of cache ports*. To investigate the sensitivity of the accelerator's power and performance to the number of cache ports, we set number of ports to 1 and sweep all other parameters; afterward, design points that improve the overall performance of the system are extracted. We perform similar sensitivity analysis for cache port sizes of 2, 4, and 8. For instance, all the green points are the designs with the cache pDeort size of 8. Similarly, sensitivity analysis for other design parameters is performed. Due to the symmetry of the trends for counterparts in each scheme, we only present the results for the Server and Signer. DSE trends over the schemes are similar; hence, we just present DSE results of NTT_CT for Kyber and NTT_GS for NewHope and Dilithium.

Sensitivity analysis. SoC components share the same system bus width and cache line size; although these two are sweepable parameters, we fixed them at 8 and 64 bytes, since they are the typical sizes of CPU and system bus. The clock frequency of the host processor and system bus are fixed at 2 GHz and 1 GHz, respectively. The frequency of the accelerator can be set to 100, 200, or 500 MHz.

Figures 8–11 shows the effect of number of cache ports (Figure 8), software pipelining (Figure 9), number of parallel lanes (Figure 10), and accelerator's cache size (Figure 11) on the power and latency of an accelerator in a scheme. *Loop pipelining* overlaps execution of instructions over different loop iterations by exploiting the loop level parallelism and can be beneficial to improve the performance but increases the hardware complexity and the energy dissipation. Software pipelining is more effective if it is being used with loop unrolling. *Loop unrolling* determines the number of parallel lanes that are created inside the accelerator for each loop. Loop unrolling improves the performance by alleviating the branch penalty and memory latency with an increase in the code size and the hardware area. Memory reduction latency needs parallel access to memory banks from the lanes, which can be achieved by increasing the number of *cache ports*; this also incurs high power consumption and area overhead.

The DSE trends for each counterpart in a scheme are similar; hence we only present the results for the Server and the Signer. Also, due to the resemblance of the DSE trends, e.g., *Kyber_Server*:

Fig. 9. The sensitivity of the accelerators' performance and power to the *software pipelining*. Software pipelining is either enabled or disabled.

Fig. 10. The sensitivity of the accelerators' performance and power to the *number of lanes*. Parallel lanes are swept in the range [1-12] for Keccak-f [1600] and [1-64] for NTT_CT and NTT_GS.

Fig. 11. The sensitivity of the accelerators' performance and power to the *cache size*. Size of the accelerator's cache is swept in the range [4kB-16kB] for all the accelerators.

NTT_CT and *Dilithium_Sign:NTT_CT*, we just present DSE results of *NTT_CT* for Kyber and *NTT_GS* for Dilithium.

Selected design points. We carried out our selection focusing first on energy consumption, then the area occupation, and, finally, the speed of each accelerator. Table 2 provides the improvement of the latency, energy, and EDP of the schemes when only one kernel is accelerated, and the rest of the scheme is executed on the CPU. After selecting the desired design points for each accelerator, they are coupled to the bus and communicate via the coherent memory hierarchy (Figure 7). Figure 12 summarizes speedup and EDP improvements of the schemes when all the calls inside of the schemes to Keccak, *NTT_CT*, and *NTT_GS* are offloaded to their corresponding optimized accelerators. The frequency of the accelerators 100, 200, and 500 MHz.

Based on the results we obtained, we can derive several general guidelines about accelerating lattice-based cryptography. Figure 9 suggests always to enable the loop pipelining, since most of the points on the Pareto-frontier curves are the blue points (pipelining on). The iterative nature of the selected kernels is the main reason for the efficacy of loop pipelining. Considering energy as the main concern, independent of the scheme, after 64 times of loop unrolling the performance gain is saturated for *NTT_CT* and *NTT_GS* (Figure 10); the saturation point for Keccak is 12 parallel lanes.

According to Figure 8, the highest speedup is achieved with eight cache ports, considering the performance as the primary concern. However, considering the energy as the primary figure of merit as is our goal, cache port 4 is suggested, because for all the kernels it achieves acceptable performance. Besides, the cache size of 4 kB is proper for all the accelerators, since with bigger cache sizes performance improvements cannot compensate for the energy penalty.

Another consideration is related to the size of the polynomial and the achieved acceleration. The bigger the size of the polynomial, the more speedup we get. NewHope1024 achieves, on average,

Table 2. Latency and Energy-delay Product (EDP) Improvement of the Schemes (Functional Units Power Models Are Based on OpenPDK 45nm and SRAM Model from CACTI 5.3); One Accelerator (100 MHz) at a Time Is Attached to the Host x86 CPU (2 GHz) through the Bus

Scheme	Kernel	Cycle Count		Speedup (CPU+Accel)	Improvement (CPU+Accel)		Accelerator's area (mm^2)
		CPU (Baseline)	CPU+Accel	Speedup	Energy	EDP	
NewHope1024cpa Server	NTT_GS		676297	1.89	1.36	2.6	1.42
	Keccak	1283366	1282400	1.01	1.06	1.07	1.64
NewHope1024cpa Client	NTT_GS	1353624	741725	1.82	1.35	2.46	1.43
	Keccak		1352716	1	1	1	1.64
Kyber768 Server	NTT_CT		1620437	1.29	1.11	1.44	0.42
	NTT_GS	2100227	1837164	1.14	1.19	1.54	1.43
	Keccak		2069412	1.1	1.05	1.07	1.64
Kyber768 Client	NTT_CT		843838	1.29	1.19	1.54	0.42
	NTT_GS	1090235	951567	1.15	1.13	1.29	1.43
	Keccak		1052613	1.03	1.13	1.17	1.64
Dilithium Sign	NTT_CT		2077058	1.18	1.07	1.45	1.36
	NTT_GS	2470672	1987848	1.24	1.09	1.28	1.46
	Keccak		2441352	1.01	1.03	1.25	1.64
Dilithium Verify	NTT_CT		1060998	1.20	1.20	1.28	1.36
	NTT_GS	1278898	1156888	1.10	1.16	1.35	1.46
	Keccak		1229706	1.04	1.20	1.05	1.64
R.EMBLEM Server	NTT_CT		2400767	1.7	1.5	2.5	1.36
	NTT_GS	4072534	3147634	1.3	1.3	1.7	1.42
R.EMBLEM Client	NTT_CT	1721429	1273543	1.34	1.26	1.7	1.36
	NTT_GS		1101269	1.56	1.43	2.24	1.42
AKCN_LWE Server	NTT_CT	1216360	933151	1.3	1.2	1.56	1.36
AKCN_LWE Client	NTT_CT	1087624	860891	1.26	1.1	1.33	1.36

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To select a design point and attach the corresponding accelerator to the SoC, we focus first on energy consumption, then the area occupation, and, finally, the speed of each accelerator.

20% more speedup than NewHope512 by using the same accelerators, since polynomials in NewHope1024 is twice bigger than NewHope512, and, hence, it gets more benefit from the software pipelining along with loop unrolling. In the case of MLWE schemes, Kyber and Dilithium, size of the polynomials are the same for all different version of the scheme; hence, the speedup for different variants of MLWE schemes is similar.

With the current fast CPU (2 GHz) and energy-efficient accelerator (Figure 12), we suggest to allow the accelerators to operate at the maximum frequency, 500 MHz, specifically for Keccak, since at 100 MHz (Table 2) it is not beneficial to use the accelerator. The power consumption of the accelerators is 2 orders of magnitude less than that of the host CPU; consequently, faster accelerators result in better EDP improvement and higher speedup.

Comparing our acceleration with state of the art is challenging, since the acceleration of these algorithms was not presented in literature before. We can, however, compare the achieved performance with results used with the same tool-chain in other domains.

Previous hardware implementations and accelerators. Hardware implementations for the analyzed algorithms are rather scarce, but proponents of R.EMBLEM designed and implemented in the Zynq-7000 board the algorithm EMBLEM.CPA (meaning without the ring structure) [32].

Fig. 12. Delay and EDP improvement of the schemes when all the accelerators (fastest design points) at different frequencies are simultaneously attached to the bus.

Their design only used 24 FFs and 48 LUTs, but this result can be misleading for evaluating the area of R.EMBLEM.CCA. The same board was used to implement NewHope for high performance. Four butterfly units were employed that use 6,680 slices, 9,412 FFs, 18,756 LUTs, 8DSP, and 14 BRAMS; the implementation took 51.9, 78.6, and 21.1 μ s for the three phases of NewHope at a frequency of 131 MHz [18]. An existing co-processor for RSA/ECC was repurposed for (ideal) lattice-based cryptography. CCA-secure Kyber768 key generation was executed in 79.6 ms, encapsulation in 102.4 ms, and decapsulation in 132.7 ms [1]. Aside from the acceleration, this work confirmed that PQC is feasible on current smart card platforms.

Kanad Basu et al. [7] compared different hardware implementations of PQC algorithms. They used Xilinx HLS-based design space exploration to map C-code to FPGA and ASIC. Differing from us, they created an accelerator with the complete algorithms; instead, we create accelerators for the bottleneck functions. Therefore, we include in our methodology a profiling step to identify the most time-consuming functions, and, hence, our accelerator implements kernels that can be used in different algorithms that result in smaller accelerator (even after a linear correction on the transistor length of the libraries). Additionally, we present the effect on energy, which is an overlooked metric in previous works.

6 CONCLUSION

In this article, we concentrate on hardware acceleration for lattice-based algorithms. Since at this stage, it is impossible to commit to a single algorithm, despite the fact that several applications

would require performance not achievable by the software-only implementation, we propose, for the first time to the best of our knowledge, to design cache-based accelerators that are programmable at two dimensions (kernel sizes data types) for hardware kernels. To this end, we presented a design flow, and we demonstrated its suitability for accelerating *NewHope*, *Kyber*, *Dilithium*, *KCL*, and *REMBLEM* five submissions to the NIST standardization contest. Our experiments demonstrated the suitability of the approach for exploring the design space of hardware accelerator for lattice-based algorithms, allowing us to quickly identify hardware kernels capable of reducing the energy consumption up to $2.1\times$ and EDP up to $5.2\times$ and improve the speedup up to $2.5\times$. Thanks to the quick exploration and performance estimation, we discover compelling guidelines for manually designing more optimized hardware accelerators for lattice-based algorithms. In the near future, we plan to extend our evaluation to evaluate more lattice-based algorithms and other families of the post-quantum schemes.

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Received March 2019; revised August 2019; accepted January 2020