Radboud University

PQ.V.ALU.E: Post-Quantum RISC-V Custom ALU Extensions on Dilithium and Kyber

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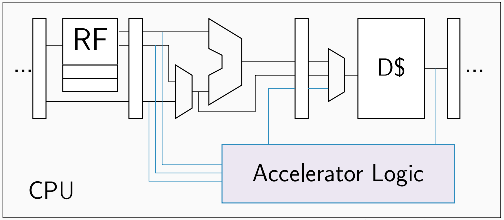
Introduction

- Context
  - Quantum computing will threaten traditional Public Key Cryptography.
  - Shift to Post-Quantum cryptography.
  - NIST standarizes: CRYSTALS-Kyber (KEM) and CRYSTALS-Dilithium (Digital Signatures).
- Challenges in implementation
  - Resource-constrained devices:
    - IoT, sensors, healthcare, automotive processors.
    - Limited computational capabilities, energy resources, memory.

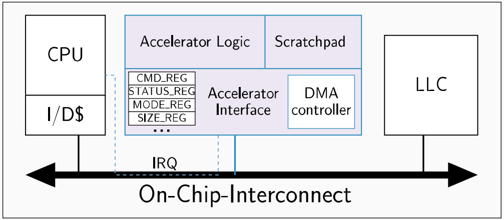
Contributions - PQ.V.ALU.E

- Custom ALU
  - Lightweight ALU for NTT computations in Dilithium and Kyber.
  - Integrated into a 4-stage pipeline 32-bit RISC-V processor.
- ISA Extension
  - Ten new instructions for modular arithmetic and NTT butterfly operations.
- Efficiency
  - Over 80% reduction in cycle count compared to optimized assembly.
  - No decrease in specific microprocessor's operating frequencies.

- Custom Extensions
  - Tailored instructions for specific applications.
- Need for Efficiency
  - HW/SW co-design strategies for performance.

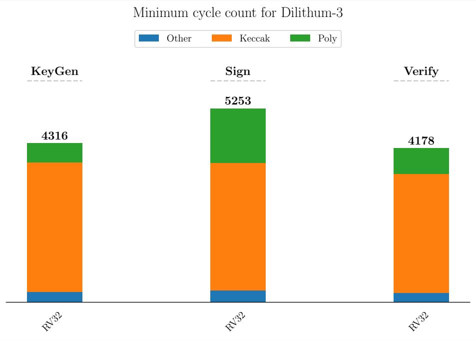


Integrated directly into the processor.(TCA)

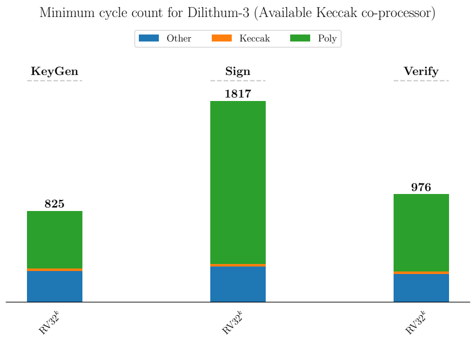


Added as peripherals to the processor.(LCA)

Dilithium Profiling



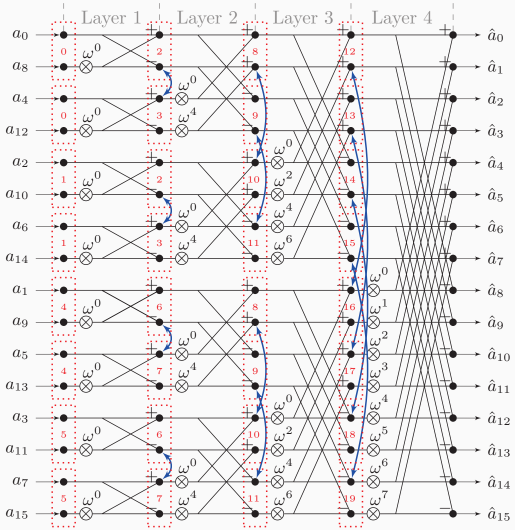
RISC-V assembly

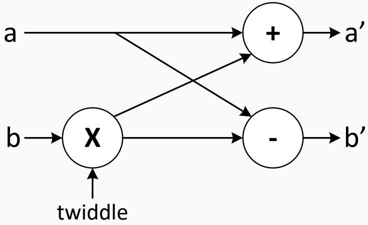


RISC-V assembly + Keccak co-processor

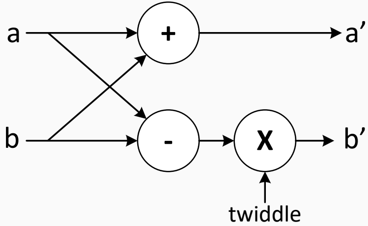
- Dominant factors
  - Keccak is a significant portion of the runtime.
  - Polynomial operations.

Number-Theoretic Transform (NTT) and butterfly operations

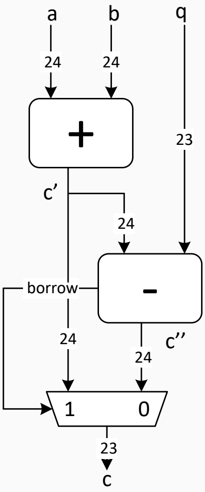




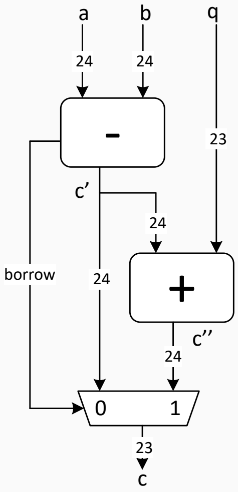
Cooley-Tukey butterlfy



Gentleman-Sande butterlfy

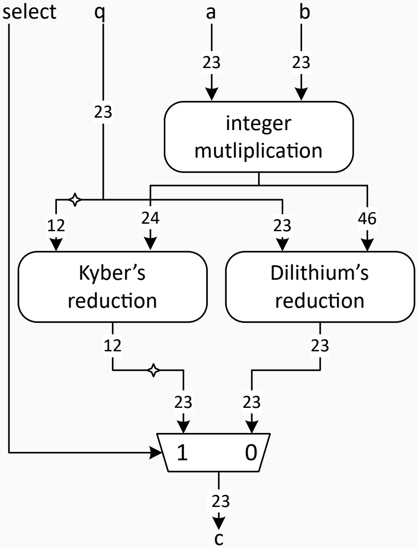


Modular Addition



Modular Substraction

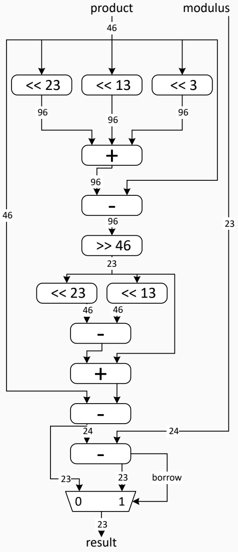
Modular multiplication



Algorithm 1 Barrett Reduction in Dilithium

Input: $0 \leq x < 8\,380\,417^2$,
Output: $z = x \mod 8\,380\,417$

1: $t \leftarrow (x \ll 23) + (x \ll 13) + (x \ll 3) - x$
2: $t \leftarrow t \gg 46$
3: $t \leftarrow (t \ll 23) - (t \ll 13) + t$
4: $z \leftarrow x - t$
5: **if** $z \geq 8\,380\,417$ **then**
6: $\quad z \leftarrow z - 8\,380\,417$
7: **return** z



Barrett reduction for Kyber

Algorithm 2 Barrett Reduction in Kyber

Input: $0 \leq x < 3329^2$,

Output: $z = x \mod 3329$

$t \leftarrow 5039 \cdot x$

$t \leftarrow t \gg 24$

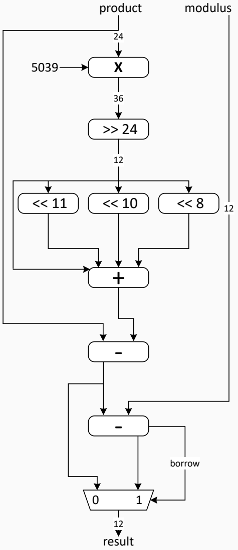
$t \leftarrow (t \ll 11) + (t \ll 10) + (t \ll 8) + t$

$z \leftarrow x - t$

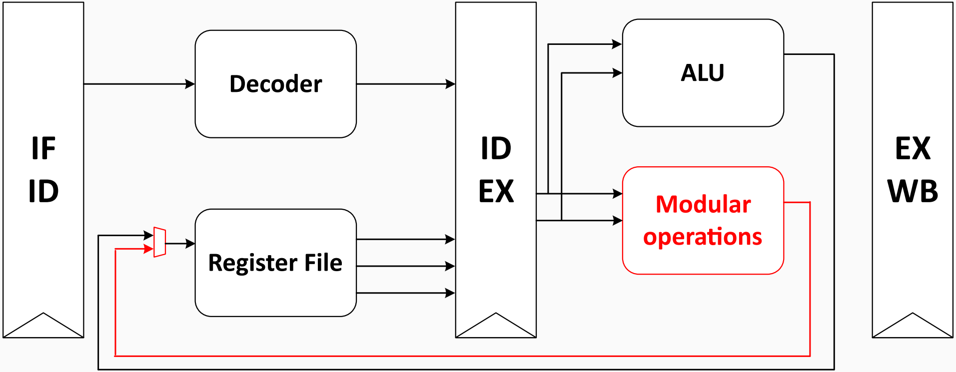
if $z \geq 3329$ **then**

  $z \leftarrow z - 3329$

return z



Modified datapath



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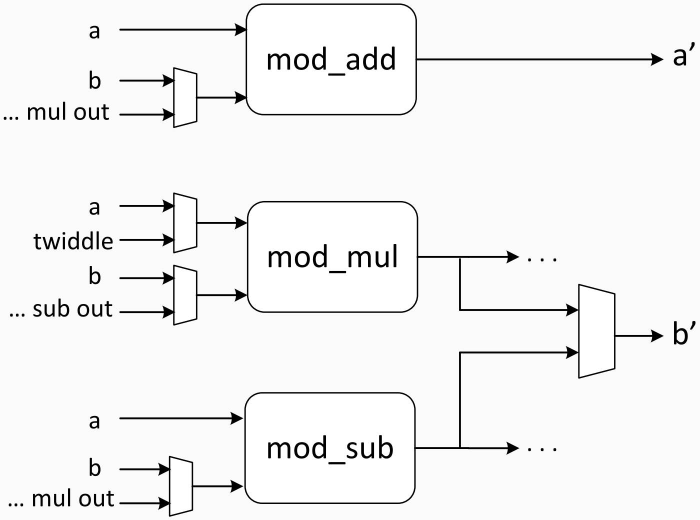
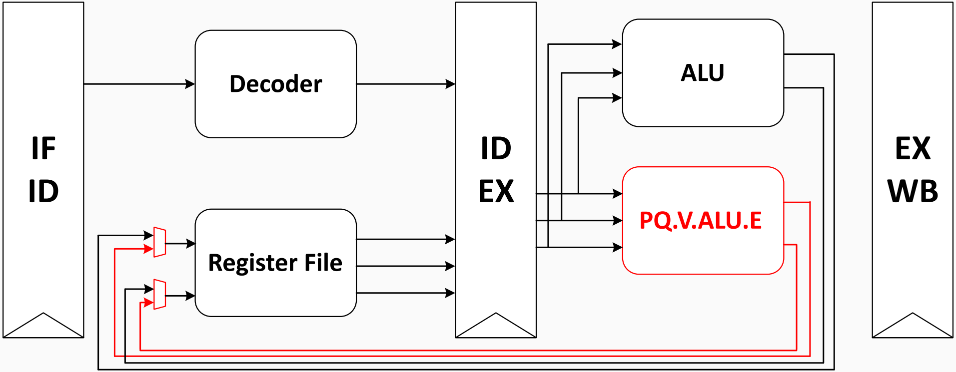

a
b
... mul out
mod_add
a’
a
twiddle
b
... sub out
mod_mul
. . .
b’
a
b
... mul out
mod_sub
. . .

Modified datapath



Custom instructions

31 25	24 20	19 15	14 12	11 7	6 0
funct7	rs2	rs1	funct3	rd	opcode

opcode	**funct3**	**funct7**	**operation name**
1110111	001	0000000	pq.mod_add_dil
1110111	010	0000000	pq.mod_sub_dil
1110111	011	0000000	pq.mod_mul_dil
1110111	100	0000000	pq.ct_btrfly_dil
1110111	101	0000000	pq.gs_btrfly_dil
1110111	001	0000001	pq.mod_add_kyb
1110111	010	0000001	pq.mod_sub_kyb
1110111	011	0000001	pq.mod_mul_kyb
1110111	100	0000001	pq.ct_btrfly_kyb
1110111	101	0000001	pq.gs_btrfly_kyb

Butterfly with custom assembly (1/2)

```
.macro montgomery al, ah, qi, q
    mul \al, \a, \qi
    mulh \al, \al, \q
    sub \al, \ah, \al
.endm

.macro ct_butterfly a, b, qi, q, zeta,
      tmp
    mul \tmp, \zeta, \b
    mulh \b, \zeta, \b
    montgomery \tmp, \b, \qi, \q
    sub \b, \a, \tmp
    add \a, \a, \tmp
.endm
```

(a) Cooley-Tukey, RV32

```
.macro montgomery al, ah, qi, q
    mul \al, \a, \qi
    mulh \al, \al, \q
    sub \al, \ah, \al
.endm

.macro gs_butterfly a, b, qi, q, zeta,
      tmp
    sub \tmp, \a, \b
    add \a, \a, \right
    mul \b, \zeta, \tmp
    mulh \tmp, \zeta, \tmp
    montgomery \b, \tmp, \qi, \q
.endm
```

(b) Gentleman-Sande, RV32

Butterfly with custom assembly (2/2)

```
.macro ct_butterfly a, b, z, tmp
    pq.mod_mul \tmp, \z, \b
    pq.mod_sub \b, \a, \tmp
    pq.mod_add \a, \a, \tmp
.endm
```

(c) Cooley-Tukey, PQVALUE[1]

```
.macro gs_butterfly a, b, zeta, tmp
    pq.mod_sub \tmp, \a, \b
    pq.mod_add \a, \a, \b
    pq.mod_mul \b, \zeta, \tmp
.endm
```

(d) Gentleman-Sande, PQVALUE[1]

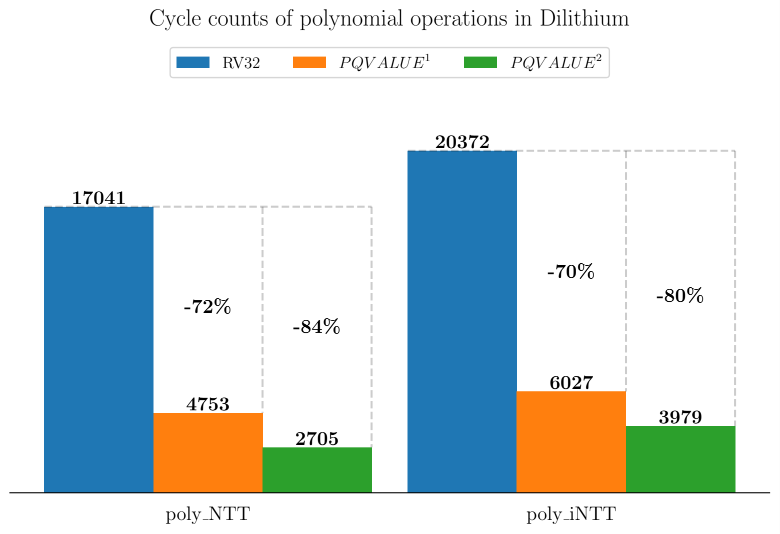
```
.macro ct_butterfly a, b, zeta
    pq.ct_btrfly \a, \b, \zeta
.endm
```

(e) Cooley-Tukey, PQVALUE[2]

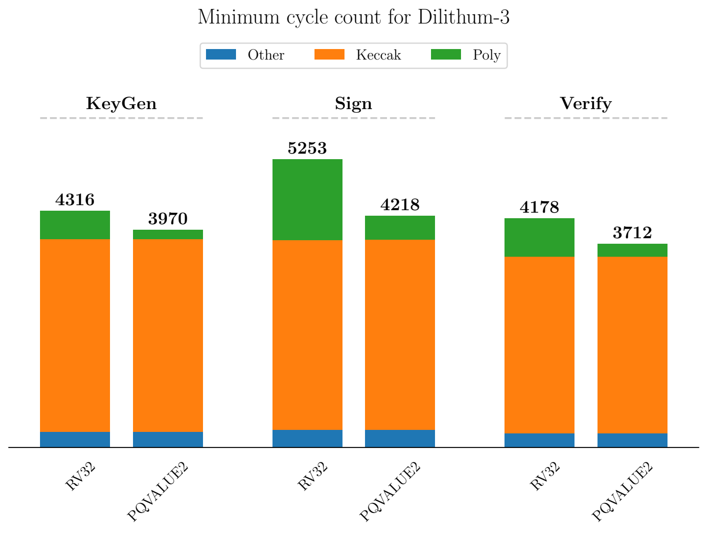
```
.macro gs_butterfly a, b, zeta, tmp
    pq.gs_btrfly \a, \b, \zeta
.endm
```

(f) Gentleman-Sande, PQVALUE[2]

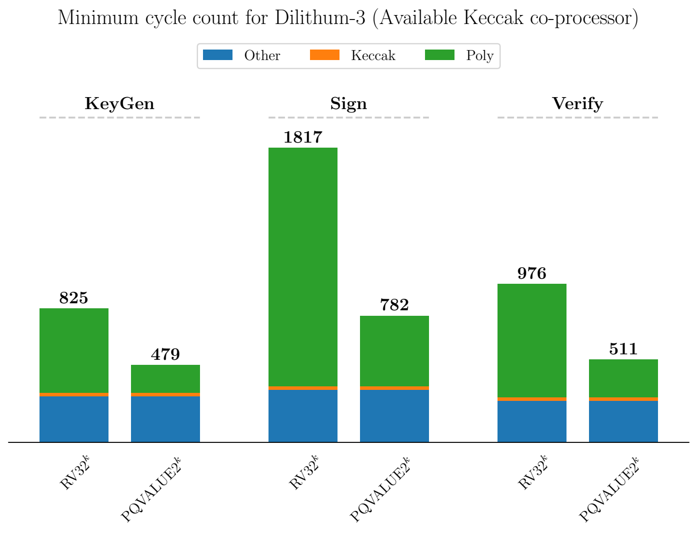
Cycles for polynomial operations



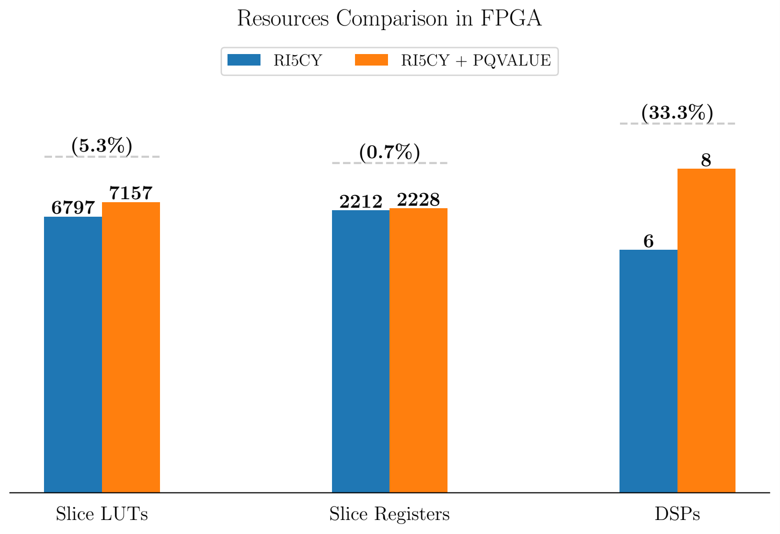
Cycles for Dilithium per phase



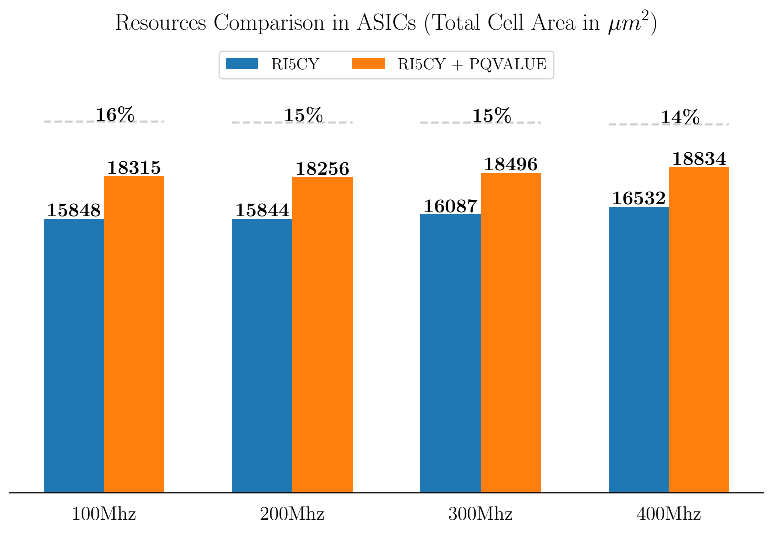
Cycles for Dilithium with Keccak co-processor



FPGA Resources



ASIC resourses



Size and efficiency comparison of post-quantum ALUs

	Resources				Kyber perf.		
	LUT	Reg.	DSP	BRAM	Core	NTT	NTT^{-1}
PQR-ALU [8]	2 908	170	9	0	RI5CY	1 935	1 930
PQ ALU [17]	555	0	15	1	CVA6	18 448	18 448
PQVALUE[2]	**459**	**0**	**2**	**0**	**RI5CY**	**2 577**	**3 851**

[8] Fritzmann, T., Sigl, G., & Sepúlveda, J. (2020). RISQ-V: Tightly Coupled RISC-V Accelerators for Post-Quantum Cryptography. IACR Transactions on Cryptographic Hardware and Embedded Systems, 2020(4), 239–280.

[17] P. Nannipieri, S. Di Matteo, L. Zulberti, F. Albicocchi, S. Saponara and L. Fanucci (2021), "A RISC-V Post Quantum Cryptography Instruction Set Extension for Number Theoretic Transform to Speed-Up CRYSTALS Algorithms," in IEEE Access, vol. 9, pp. 150798-150808.

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