Energy Consumption of Round 2 Submissions for NIST PQC Standards

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Motivation

- Round 2 candidates for NIST Post-Quantum Cryptography (PQC) standardization process includes 17 Key Encapsulation Mechanisms (KEM) and 9 Digital Signature schemes for consideration

- Submissions are to be evaluated based on correctness, speed, and storage requirements

- Due to increased use of battery-operated devices and growing interest in green-computing, energy consumed by candidate submissions is also important to consider

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Motivation

Goal

To profile all Round 2 PQC submissions for energy consumption, categorized by proposed security level, from which we can rank the candidates and determine which schemes are most energy efficient

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Outline

1. Goal and Motivation
2. Categorization of NIST PQC Round 2 Candidates
3. Methodology
4. Energy Profile of Optimized C Implementations
5. Energy Profile of Assembly Optimized Implementations
6. Ranking of Optimized C Implementations vs. Ranking of Assembly Optimized Implementations
7. Summary and Future Work

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Categorization of KEM/PKE Submissions

Scheme	Lattice	Code	Isogeny	Rank
BIKE		✓		
Classic McEliece		✓		
CRYSTALS-Kyber	✓			
FrodoKEM	✓			
HQC		✓		
LAC	✓			
LEDAcrypt		✓		
NewHope	✓			
NTRU	✓			
NTRU Prime	✓			
NTS-KEM		✓		
ROLLO				✓
Round5	✓			
RQC				✓
SABER	✓			
SIKE			✓	
Three Bears	✓			

Table 1: Categorization of **Key Encapsulation / Public-Key Encryption** schemes based on the mathematics of the cryptosystem

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Categorization of Digital Signature Submissions

Scheme	Lattice	Multivariate	Other
CRYSTALS-Dilithium	✓		
Falcon	✓		
GeMSS		✓	
LUOV		✓	
MQDSS		✓	
Picnic			✓
qTESLA	✓		
Rainbow		✓	
SPHINCS+			✓

Table 2: Categorization of **Digital Signature** schemes based on the mathematics of the cryptosystem

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Additional Implementations of KEM/PKE Submissions

Scheme	x86 Assembly Optimization			Other Hardware		
	SIMD	AES-NI	Other	ARM	FPGA	ASIC
BIKE	✓	✓	✓		✓	
Classic McEliece	✓					
CRYSTALS-Kyber	✓	✓				
FrodoKEM	✓	✓		✓		
HQC	✓					
LAC	✓					
LEDAcrypt	✓					
NewHope	✓					
NTRU	✓					
NTRU Prime						
NTS-KEM	✓		✓			
ROLLO						
Round5	✓					
RQC						
SABER	✓	✓				
SIKE			✓	✓	✓	✓
Three Bears			✓			

Table 3: Additional implementations submitted in Round 2 packages of **Key Encapsulation / Public-Key Encryption** schemes

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Additional Implementations of Digital Signature Submissions

Scheme	x86 Assembly Optimization			Other Hardware		
	SIMD	AES-NI	Other	ARM	FPGA	ASIC
CRYSTALS-Dilithium	✓	✓				
Falcon						
GeMSS	✓		✓			
LUOV	✓					
MQDSS	✓					
Picnic	✓			✓		
qTESLA	✓					
Rainbow	✓					
SPHINCS+	✓	✓				

Table 4: Additional implementations submitted in Round 2 packages of **Digital Signature** schemes

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Methodology

- IgProf lightweight profiler used to capture energy measurements which operates on the principal of statistical sampling
- Uses PAPI to obtain measurements from the Running Average Power Limit at a fixed interval
- Attributes the current energy measurement to the present location of execution of the code being profiled
- Creates a flat cumulative profile, flat self profile, and call graph profile
- This can help pinpoint most energy consuming functions and their subroutines

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Methodology

- IgProf lightweight profiler used to capture energy measurements
- Operates on the principal of statistical sampling
- U… …age P…
- A… I…
- C… …aph p…
- T… …nd their subroutines

```
------------------------------------------------------------------------
Call tree profile (cumulative)

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Rank    % total       Self       Self / Children   Function

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
          100.0  .........     187.01 / 187.01       __libc_start_main [3]
[4]       100.0     187.01       0.00 / 187.01     main
           80.9  .........     151.26 / 151.26       crypto_sign_open [8]
           17.7  .........      33.11 / 33.11        crypto_sign [13]
            0.8  .........       1.52 / 1.52         crypto_sign_keypair [25]
```

NIST API

Methodology

- Optimized C Implementations were built on a 64-bit processor Intel Xeon E3-1270 CPU @ 3.40GHz with 8GB of RAM running Ubuntu 16.04 LTS

- Assembly Optimized Implementations were built on a 64-bit processor Intel Core i7-6700 CPU @ 3.40GHz with 8GB of RAM running Ubuntu 16.04 LTS

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Methodology

- Optimized C Implementations were built on a 64-bit processor Intel Xeon E3-1270 CPU @ 3.40GHz with 8GB of RAM running Ubuntu 16.04 LTS

- Assembly Optimized Implementations were built on a 64-bit processor Intel Core i7-6700 CPU @ 3.40GHz with 8GB of RAM running Ubuntu 16.04 LTS

- For operations requiring a message, 100 random messages were created of fixed length, where the length was chosen to be approximately the same as the maximum tested in NIST'S provided KAT scripts
  - 32 byte messages for PKE schemes
  - 3300 byte messages for Digital Signature schemes

- Minimum of 100 iterations

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Results for Optimized C Implementation

Key Encapsulation Mechanisms

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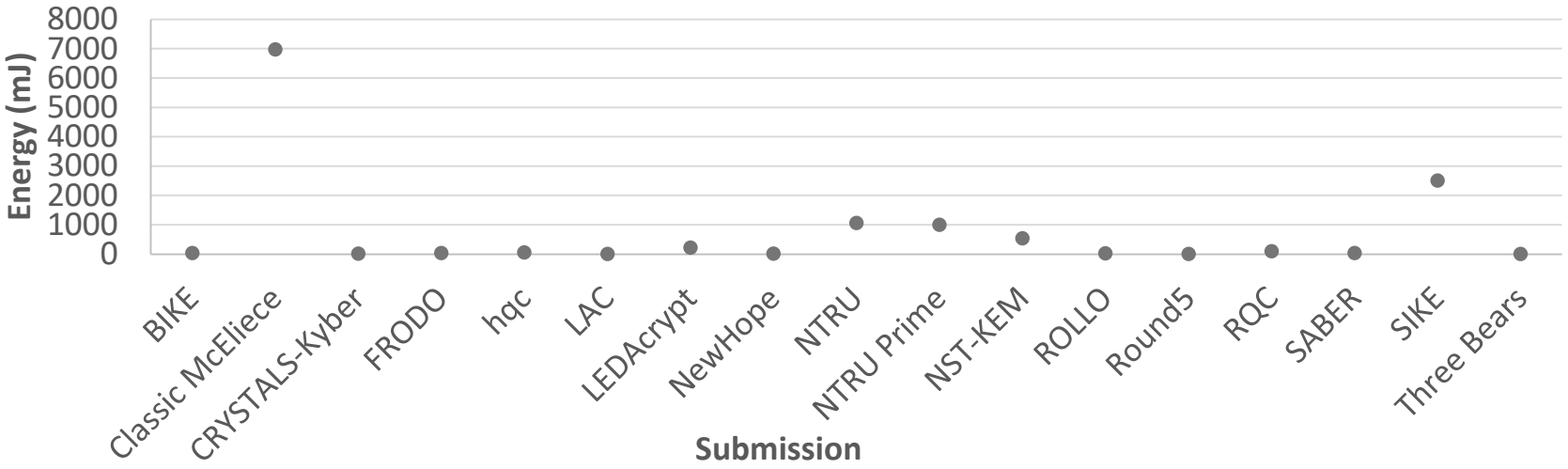
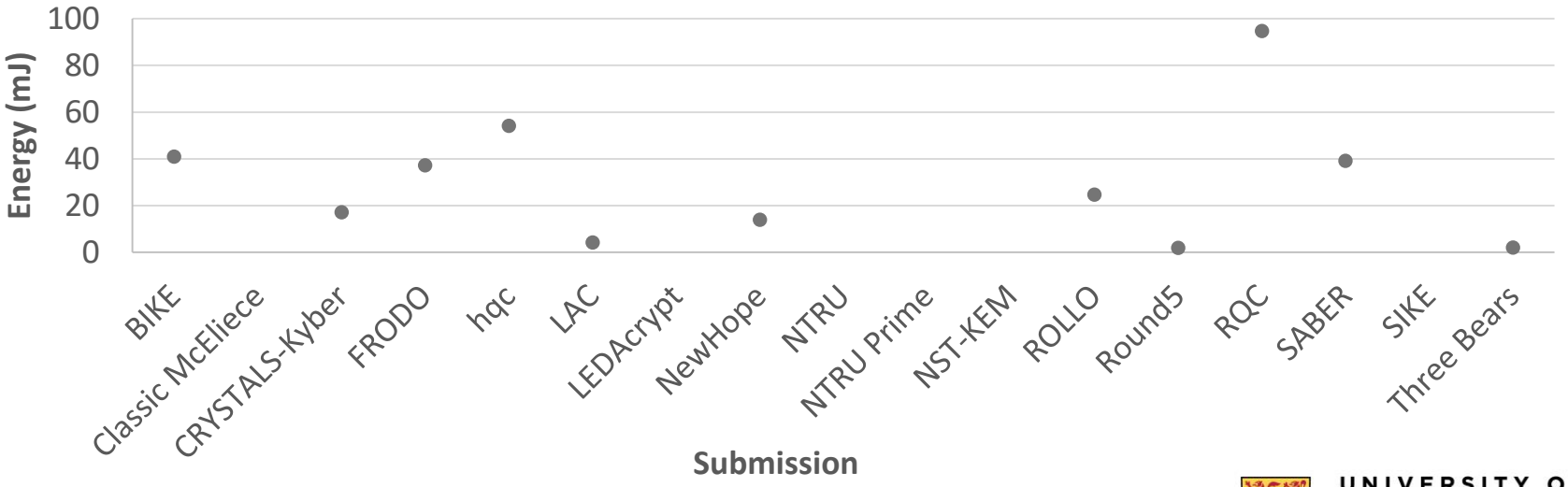
Total Energy Consumed by KEM Targeting Level 1



Total Energy Consumed by KEM Targeting Level 1 (below 100 mJ)



Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE-1 CCA	5.63	-	17.62	-	39.37
BIKE-1 CPA	5.02	-	13.62	-	24.25
BIKE-2 CCA	11.85	-	38.29	-	85.95
BIKE-2 CPA	10.51	-	28.85	-	49.29
BIKE-3 CCA	3.29	-	10.67	-	22.66
BIKE-3 CPA	3.15	-	8.05	-	18.28
Classic McEliece	6384.90	-	11632.40	-	38234.60
CRYSTALS-Kyber	4.15	-	7.20	-	11.29
CRYSTALS-Kyber-90s	6.86	-	12.58	-	21.03
FRODO AES	10.27	-	30.20	-	28.07
FRODO SHAKE	9.36	-	29.22	-	28.51
hqc-1	8.76	-	23.41	-	35.62
hqc-2	-	-	25.68	-	43.83
hqc-3	-	-	-	-	49.80
LAC	0.88	-	2.63	-	2.80
LEDAcrypt N02	407.20	-	860.30	-	1799.00
LEDAcrypt N03	103.00	-	387.80	-	1024.80
LEDAcrypt N04	102.40	-	333.30	-	771.00
LEDAcrypt LT DFR64	9359.50	-	30104.60	-	96421.70
LEDAcrypt LT DFRSL	15088.90	-	55077.80	-	155391.90
NewHope CCA	5.42	-	-	-	10.76
NewHope CPA	4.99	-	-	-	9.94
NTRU-HPS	989.52	-	1784.32	-	2673.23
NTRU-HRSS	-	-	1922.05	-	-
sNTRU Prime	-	1600.31	2102.77	2628.83	-
NTRU LPrime	-	182.74	242.94	313.77	-
NTS-KEM	535.30	-	1863.40	-	2886.20
ROLLO-I	16.37	-	26.18	-	31.83
ROLLO-II	116.18	-	127.65	-	126.03
ROLLO-III	3.45	-	4.82	-	6.75
Round5 Ring	0.57	-	1.87	-	2.36
Round5 Ring 5	0.67	-	1.26	-	2.29
Round5 Ring Long Key	0.73	-	-	-	-
Round5 Non-Ring	52.83	-	133.90	-	236.69
RQC	6.30	-	10.51	-	16.83
SABER	1.13	-	2.40	-	3.95
SIKE	573.80	884.70	1682.90	-	2859.90
SIKE Compressed	1461.90	2102.40	4034.50	-	6750.80
Three Bears	-	0.73	-	1.41	2.35
Three Bears Eph.	-	0.74	-	1.45	2.55

Table 5: Energy consumption of **`crypto_kem_keypair`** function for **Keypair Generation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE-1 CCA	5.63	-	17.62	-	39.37
BIKE-1 CPA	5.02	-	13.62	-	24.25
BIKE-2 CCA	11.85	-	38.29	-	85.95
BIKE-2 CPA	10.51	-	28.85	-	49.29
BIKE-3 CCA	3.29	-	10.67	-	22.66
BIKE-3 CPA	3.15	-	8.05	-	18.28
Classic McEliece	6384.90	-	11632.40	-	38234.60
CRYSTALS-Kyber	4.15	-	7.20	-	11.29
CRYSTALS-Kyber-90s	6.86	-	12.58	-	21.03
FRODO AES	10.27	-	30.20	-	28.07
FRODO SHAKE	9.36	-	29.22	-	28.51
hqc-1	8.76	-	23.41	-	35.62
hqc-2	-	-	25.68	-	43.83
hqc-3	-	-	-	-	49.80
LAC	0.88	-	2.63	-	2.80
LEDAcrypt N02	407.20	-	860.30	-	1799.00
LEDAcrypt N03	103.00	-	387.80	-	1024.80
LEDAcrypt N04	102.40	-	333.30	-	771.00
LEDAcrypt LT DFR64	9359.50	-	30104.60	-	96421.70
LEDAcrypt LT DFRSL	15088.90	-	55077.80	-	155391.90
NewHope CCA	5.42	-	-	-	10.76
NewHope CPA	4.99	-	-	-	9.94
NTRU-HPS	989.52	-	1784.32	-	2673.23
NTRU-HRSS	-	-	1922.05	-	-
sNTRU Prime	-	1600.31	2102.77	2628.83	-
NTRU LPrime	-	182.74	242.94	313.77	-
NTS-KEM	535.30	-	1863.40	-	2886.20
ROLLO-I	16.37	-	26.18	-	31.83
ROLLO-II	116.18	-	127.65	-	126.03
ROLLO-III	3.45	-	4.82	-	6.75
Round5 Ring	0.57	-	1.87	-	2.36
Round5 Ring 5	0.67	-	1.26	-	2.29
Round5 Ring Long Key	0.73	-	-	-	-
Round5 Non-Ring	52.83	-	133.90	-	236.69
RQC	6.30	-	10.51	-	16.83
SABER	1.13	-	2.40	-	3.95
SIKE	573.80	884.70	1682.90	-	2859.90
SIKE Compressed	1461.90	2102.40	4034.50	-	6750.80
Three Bears	-	0.73	-	1.41	2.35
Three Bears Eph.	-	0.74	-	1.45	2.55

Table 5: Energy consumption of **`crypto_kem_keypair`** function for **Keypair Generation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE-1 CCA	6.83	-	20.21	-	48.65
BIKE-1 CPA	5.94	-	15.20	-	26.53
BIKE-2 CCA	2.70	-	8.75	-	21.54
BIKE-2 CPA	2.36	-	5.86	-	11.06
BIKE-3 CCA	5.55	-	18.82	-	45.70
BIKE-3 CPA	4.85	-	13.74	-	34.70
Classic McEliece	1.84	-	3.09	-	4.81
CRYSTALS-Kyber	6.00	-	9.13	-	14.62
CRYSTALS-Kyber-90s	7.62	-	13.94	-	21.10
FRODO AES	14.71	-	32.20	-	47.96
FRODO SHAKE	13.97	-	30.88	-	48.53
hqc-1	18.42	-	42.92	-	65.85
hqc-2	-	-	41.81	-	76.53
hqc-3	-	-	-	-	87.53
LAC	1.28	-	3.53	-	4.58
LEDAcrypt N02	20.14	-	47.00	-	81.90
LEDAcrypt N03	15.90	-	38.10	-	88.00
LEDAcrypt N04	20.87	-	49.70	-	101.90
LEDAcrypt LT DFR64	70.50	-	137.40	-	234.00
LEDAcrypt LT DFRSL	115.50	-	291.00	-	526.30
NewHope CCA	8.19	-	-	-	16.57
NewHope CPA	7.47	-	-	-	12.56
NTRU-HPS	22.21	-	36.35	-	48.03
NTRU-HRSS	-	-	33.59	-	-
sNTRU Prime	-	177.50	236.95	300.36	-
NTRU LPrime	-	330.60	450.95	586.52	-
NTS-KEM	0.92	-	3.55	-	4.66
ROLLO-I	3.63	-	5.21	-	6.62
ROLLO-II	18.71	-	25.06	-	22.81
ROLLO-III	8.60	-	10.24	-	16.02
Round5 Ring	0.93	-	3.09	-	3.88
Round5 Ring 5	1.14	-	1.86	-	3.38
Round5 Ring Long Key	1.18	-	-	-	-
Round5 Non-Ring	47.47	-	118.22	-	222.17
RQC	12.86	-	23.67	-	36.61
SABER	19.04	-	29.63	-	46.32
SIKE	934.10	1444.90	3056.10	-	4598.90
SIKE Compressed	1747.20	2619.30	4808.90	-	8492.00
Three Bears	-	0.98	-	1.52	2.52
Three Bears Eph.	-	0.93	-	1.83	2.41

Table 6: Energy consumption of **`crypto_kem_enc`** function for **Encapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE-1 CCA	6.83	-	20.21	-	48.65
BIKE-1 CPA	5.94	-	15.20	-	26.53
BIKE-2 CCA	2.70	-	8.75	-	21.54
BIKE-2 CPA	2.36	-	5.86	-	11.06
BIKE-3 CCA	5.55	-	18.82	-	45.70
BIKE-3 CPA	4.85	-	13.74	-	34.70
Classic McEliece	1.84	-	3.09	-	4.81
CRYSTALS-Kyber	6.00	-	9.13	-	14.62
CRYSTALS-Kyber-90s	7.62	-	13.94	-	21.10
FRODO AES	14.71	-	32.20	-	47.96
FRODO SHAKE	13.97	-	30.88	-	48.53
hqc-1	18.42	-	42.92	-	65.85
hqc-2	-	-	41.81	-	76.53
hqc-3	-	-	-	-	87.53
LAC	1.28	-	3.53	-	4.58
LEDAcrypt N02	20.14	-	47.00	-	81.90
LEDAcrypt N03	15.90	-	38.10	-	88.00
LEDAcrypt N04	20.87	-	49.70	-	101.90
LEDAcrypt LT DFR64	70.50	-	137.40	-	234.00
LEDAcrypt LT DFRSL	115.50	-	291.00	-	526.30
NewHope CCA	8.19	-	-	-	16.57
NewHope CPA	7.47	-	-	-	12.56
NTRU-HPS	22.21	-	36.35	-	48.03
NTRU-HRSS	-	-	33.59	-	-
sNTRU Prime	-	177.50	236.95	300.36	-
NTRU LPrime	-	330.60	450.95	586.52	-
NTS-KEM	0.92	-	3.55	-	4.66
ROLLO-I	3.63	-	5.21	-	6.62
ROLLO-II	18.71	-	25.06	-	22.81
ROLLO-III	8.60	-	10.24	-	16.02
Round5 Ring	0.93	-	3.09	-	3.88
Round5 Ring 5	1.14	-	1.86	-	3.38
Round5 Ring Long Key	1.18	-	-	-	-
Round5 Non-Ring	47.47	-	118.22	-	222.17
RQC	12.86	-	23.67	-	36.61
SABER	19.04	-	29.63	-	46.32
SIKE	934.10	1444.90	3056.10	-	4598.90
SIKE Compressed	1747.20	2619.30	4808.90	-	8492.00
Three Bears	-	0.98	-	1.52	2.52
Three Bears Eph.	-	0.93	-	1.83	2.41

Table 6: Energy consumption of `crypto_kem_enc` function for **Encapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE-1 CCA	60.10	-	132.60	-	364.80
BIKE-1 CPA	29.10	-	89.00	-	213.90
BIKE-2 CCA	46.30	-	119.60	-	270.70
BIKE-2 CPA	31.80	-	83.00	-	185.00
BIKE-3 CCA	57.90	-	140.00	-	331.70
BIKE-3 CPA	33.00	-	97.60	-	216.60
Classic McEliece	588.10	-	1497.50	-	2625.30
CRYSTALS-Kyber	7.05	-	10.51	-	14.62
CRYSTALS-Kyber-90s	9.47	-	16.10	-	23.25
FRODO AES	12.28	-	29.30	-	41.20
FRODO SHAKE	15.90	-	33.90	-	40.10
hqc-1	27.03	-	64.69	-	100.60
hqc-2	-	-	70.26	-	124.78
hqc-3	-	-	-	-	145.55
LAC	2.14	-	5.56	-	7.00
LEDAcrypt N02	105.30	-	225.10	-	391.70
LEDAcrypt N03	98.80	-	240.20	-	496.70
LEDAcrypt N04	148.50	-	354.20	-	539.40
LEDAcrypt LT DFR64	96.90	-	196.10	-	380.00
LEDAcrypt LT DFRSL	105.50	-	279.80	-	534.10
NewHope CCA	8.10	-	-	-	18.76
NewHope CPA	1.45	-	-	-	2.78
NTRU-HPS	54.36	-	98.28	-	137.03
NTRU-HRSS	-	-	100.51	-	-
sNTRU Prime	-	507.96	703.16	877.00	-
NTRU LPrime	-	483.38	657.76	851.96	-
NTS-KEM	6.32	-	12.76	-	27.74
ROLLO-I	13.31	-	25.09	-	40.53
ROLLO-II	52.76	-	64.58	-	75.37
ROLLO-III	12.63	-	25.55	-	40.03
Round5 Ring	0.39	-	1.73	-	2.24
Round5 Ring 5	0.66		1.04		1.78
Round5 Ring Long Key	0.54	-	-	-	-
Round5 Non-Ring	2.98	-	4.91	-	1.87
RQC	75.54	-	176.17	-	273.43
SABER	19.04	-	33.22	-	51.68
SIKE	999.30	1543.40	3104.50	-	4983.70
SIKE Compressed	1648.10	2417.50	4636.90	-	7880.20
Three Bears	-	1.40	-	2.25	3.54
Three Bears Eph.	-	0.44	-	0.63	0.71

Table 7: Energy consumption of **`crypto_kem_dec`** function for **Decapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE-1 CCA	60.10	-	132.60	-	364.80
BIKE-1 CPA	29.10	-	89.00	-	213.90
BIKE-2 CCA	46.30	-	119.60	-	270.70
BIKE-2 CPA	31.80	-	83.00	-	185.00
BIKE-3 CCA	57.90	-	140.00	-	331.70
BIKE-3 CPA	33.00	-	97.60	-	216.60
Classic McEliece	588.10	-	1497.50	-	2625.30
CRYSTALS-Kyber	7.05	-	10.51	-	14.62
CRYSTALS-Kyber-90s	9.47	-	16.10	-	23.25
FRODO AES	12.28	-	29.30	-	41.20
FRODO SHAKE	15.90	-	33.90	-	40.10
hqc-1	27.03	-	64.69	-	100.60
hqc-2	-	-	70.26	-	124.78
hqc-3	-	-	-	-	145.55
LAC	2.14	-	5.56	-	7.00
LEDAcrypt N02	105.30	-	225.10	-	391.70
LEDAcrypt N03	98.80	-	240.20	-	496.70
LEDAcrypt N04	148.50	-	354.20	-	539.40
LEDAcrypt LT DFR64	96.90	-	196.10	-	380.00
LEDAcrypt LT DFRSL	105.50	-	279.80	-	534.10
NewHope CCA	8.10	-	-	-	18.76
NewHope CPA	1.45	-	-	-	2.78
NTRU-HPS	54.36	-	98.28	-	137.03
NTRU-HRSS	-	-	100.51	-	-
sNTRU Prime	-	507.96	703.16	877.00	-
NTRU LPrime	-	483.38	657.76	851.96	-
NTS-KEM	6.32	-	12.76	-	27.74
ROLLO-I	13.31	-	25.09	-	40.53
ROLLO-II	52.76	-	64.58	-	75.37
ROLLO-III	12.63	-	25.55	-	40.03
Round5 Ring	0.39	-	1.73	-	2.24
Round5 Ring 5	0.66		1.04		1.78
Round5 Ring Long Key	0.54	-	-	-	-
Round5 Non-Ring	2.98	-	4.91	-	1.87
RQC	75.54	-	176.17	-	273.43
SABER	19.04	-	33.22	-	51.68
SIKE	999.30	1543.40	3104.50	-	4983.70
SIKE Compressed	1648.10	2417.50	4636.90	-	7880.20
Three Bears	-	1.40	-	2.25	3.54
Three Bears Eph.	-	0.44	-	0.63	0.71

Table 7: Energy consumption of **`crypto_kem_dec`** function for **Decapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Results for Optimized C Implementation

Public-Key Encryption Schemes

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Table 8: Energy consumption of **`crypto_encrypt_keypair`** function for **Keypair Generation** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	7944.20	29007.10	85229.90
LEDAcrypt DFRSL	11944.40	42496.40	127181.70
LAC	0.85	2.61	2.83

Table 9: Energy consumption of **`crypto_encrypt`** function for **Encryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	10.98	18.76	33.99
LEDAcrypt DFRSL	15.26	36.86	57.75
LAC	1.43	3.32	4.63

Table 10: Energy consumption of **`crypto_encrypt_open`** function for **Decryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	30.95	57.40	113.34
LEDAcrypt DFRSL	44.40	94.63	179.09
LAC	0.66	2.39	2.12

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Table 8: Energy consumption of **`crypto_encrypt_keypair`** function for **Keypair Generation** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	7944.20	29007.10	85229.90
LEDAcrypt DFRSL	11944.40	42496.40	127181.70
LAC	0.85	2.61	2.83

Table 9: Energy consumption of **`crypto_encrypt`** function for **Encryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	10.98	18.76	33.99
LEDAcrypt DFRSL	15.26	36.86	57.75
LAC	1.43	3.32	4.63

Highest energy per level

Lowest energy per level

Table 10: Energy consumption of **`crypto_encrypt_open`** function for **Decryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	30.95	57.40	113.34
LEDAcrypt DFRSL	44.40	94.63	179.09
LAC	0.66	2.39	2.12

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Results for Optimized C Implementation

Digital Signature Schemes

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	1.51	1.65	1.49	1.47	-
CRYSTALS-Dilithium AES	3.28	5.44	8.73	11.46	-
Falcon	189.80	-	-	-	537.60
GeMSS	552.20	-	3255.20	-	9738.20
BlueGeMSS	539.10	-	3106.30	-	9076.60
RedGeMSS	512.20	-	2798.60	-	8520.70
Luov Small Sig Chacha	-	105.80	-	412.50	745.20
Luov Small Sig Keccak	-	126.80	-	496.90	828.20
Luov Large Sig Chacha	-	69.30	-	187.50	455.80
Luov Large Sig Keccak	-	82.90	-	218.40	532.30
MQDSS	-	27.63	-	57.60	-
Picnic UR	0.23	-	0.33	-	0.45
Picnic FS	0.24	-	0.33	-	0.44
Picnic2 FS	0.22	-	0.34	-	0.45
qTESLA	10.04	50.24	28.36	-	146.03
qTESLA-s	10.25	51.06	28.78	-	152.73
qTESLA-p	63.55	-	226.51	-	-
qTESLA-size	-	-	-	-	228.22
qTESLA-size-s	-	-	-	-	209.51
Rainbow Classic	229.50	-	3361.80	-	8411.50
Rainbow Compressed/Cyclic	253.50	-	3714.70	-	9010.50
Rainbow Cyclic	272.80	-	4058.50	-	9320.00
SPHINCS+ SHA256 s simple	1761.00	-	2524.20	-	3501.40
SPHINCS+ SHA256 s robust	3516.90	-	5296.00	-	9586.10
SPHINCS+ SHA256 f simple	48.10	-	81.10	-	212.00
SPHINCS+ SHA256 f robust	108.70	-	151.80	-	615.40
SPHINCS+ SHAKE256 s simple	3019.90	-	4044.10	-	5446.20
SPHINCS+ SHAKE256 s robust	5174.00	-	7608.60	-	10754.80
SPHINCS+ SHAKE256 f simple	83.80	-	123.60	-	342.20
SPHINCS+ SHAKE256 f robust	171.80	-	237.90	-	652.00
SPHINCS+ HARAKA s simple	4745.70	6759.60	-	-	-
SPHINCS+ HARAKA s robust	6965.70	10444.40	-	-	-
SPHINCS+ HARAKA f simple	143.80	214.80	-	-	-
SPHINCS+ HARAKA f robust	219.30	320.10	-	-	-

Table 11: Energy consumption of **`crypto_sign_keypair`** function for **Keypair Generation** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	1.51	1.65	1.49	1.47	-
CRYSTALS-Dilithium AES	3.28	5.44	8.73	11.46	-
Falcon	189.80	-	-	-	537.60
GeMSS	552.20	-	3255.20	-	9738.20
BlueGeMSS	539.10	-	3106.30	-	9076.60
RedGeMSS	512.20	-	2798.60	-	8520.70
Luov Small Sig Chacha	-	105.80	-	412.50	745.20
Luov Small Sig Keccak	-	126.80	-	496.90	828.20
Luov Large Sig Chacha	-	69.30	-	187.50	455.80
Luov Large Sig Keccak	-	82.90	-	218.40	532.30
MQDSS	-	27.63	-	57.60	-
Picnic UR	0.23	-	0.33	-	0.45
Picnic FS	0.24	-	0.33	-	0.44
Picnic2 FS	0.22	-	0.34	-	0.45
qTESLA	10.04	50.24	28.36	-	146.03
qTESLA-s	10.25	51.06	28.78	-	152.73
qTESLA-p	63.55	-	226.51	-	-
qTESLA-size	-	-	-	-	228.22
qTESLA-size-s	-	-	-	-	209.51
Rainbow Classic	229.50	-	3361.80	-	8411.50
Rainbow Compressed/Cyclic	253.50	-	3714.70	-	9010.50
Rainbow Cyclic	272.80	-	4058.50	-	9320.00
SPHINCS+ SHA256 s simple	1761.00	-	2524.20	-	3501.40
SPHINCS+ SHA256 s robust	3516.90	-	5296.00	-	9586.10
SPHINCS+ SHA256 f simple	48.10	-	81.10	-	212.00
SPHINCS+ SHA256 f robust	108.70	-	151.80	-	615.40
SPHINCS+ SHAKE256 s simple	3019.90	-	4044.10	-	5446.20
SPHINCS+ SHAKE256 s robust	5174.00	-	7608.60	-	10754.80
SPHINCS+ SHAKE256 f simple	83.80	-	123.60	-	342.20
SPHINCS+ SHAKE256 f robust	171.80	-	237.90	-	652.00
SPHINCS+ HARAKA s simple	4745.70	6759.60	-	-	-
SPHINCS+ HARAKA s robust	6965.70	10444.40	-	-	-
SPHINCS+ HARAKA f simple	143.80	214.80	-	-	-
SPHINCS+ HARAKA f robust	219.30	320.10	-	-	-

Table 11: Energy consumption of **`crypto_sign_keypair`** function for **Keypair Generation** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	7.92	8.63	8.09	8.02	-
CRYSTALS-Dilithium AES	11.82	19.56	30.75	29.34	-
Falcon	6.40	-	-	-	16.61
GeMSS	17800.40	-	69223.60	-	142192.80
BlueGeMSS	2733.50	-	10449.80	-	17805.80
RedGeMSS	66.20	-	255.20	-	497.60
Luov Small Sig Chacha	-	39.80	-	98.20	176.20
Luov Small Sig Keccak	-	66.50	-	171.40	267.90
Luov Large Sig Chacha	-	207.40	-	568.00	1286.90
Luov Large Sig Keccak	-	222.60	-	623.10	1406.90
MQDSS	-	1219.10	-	3800.20	-
Picnic UR	137.10	-	365.90	-	673.10
Picnic FS	103.80	-	262.70	-	477.00
Picnic2 FS	3865.00	-	11413.50	-	24415.60
qTESLA	5.12	13.68	8.47	-	23.30
qTESLA-s	5.39	14.43	8.66	-	24.21
qTESLA-p	30.77	-	82.96	-	
qTESLA-size	-	-	-	-	31.30
qTESLA-size-s	-	-	-	-	33.17
Rainbow Classic	2.89	-	25.53	-	51.66
Rainbow Compressed/Cyclic	3.83	-	1902.70	-	4482.50
Rainbow Cyclic	3.22	-	24.75	-	54.97
SPHINCS+ SHA256 s simple	26494.90	-	63668.10	-	45710.80
SPHINCS+ SHA256 s robust	49013.50	-	120274.90	-	118541.20
SPHINCS+ SHA256 f simple	1799.70	-	2368.80	-	5236.80
SPHINCS+ SHA256 f robust	3446.70	-	4422.90	-	14426.20
SPHINCS+ SHAKE256 s simple	43964.30	-	86931.90	-	65658.40
SPHINCS+ SHAKE256 s robust	73310.80	-	148952.00	-	121794.40
SPHINCS+ SHAKE256 f simple	2926.10	-	3638.40	-	8049.60
SPHINCS+ SHAKE256 f robust	5257.30	-	6715.30	-	14767.70
SPHINCS+ HARAKA s simple	85968.10	184990.60	-	-	-
SPHINCS+ HARAKA s robust	130367.00	320977.50	-	-	-
SPHINCS+ HARAKA f simple	5367.00	6287.40	-	-	-
SPHINCS+ HARAKA f robust	8171.70	9742.30	-	-	-

Table 12: Energy consumption of `crypto_sign` function for **Signing** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	7.92	8.63	8.09	8.02	-
CRYSTALS-Dilithium AES	11.82	19.56	30.75	29.34	-
Falcon	6.40	-	-	-	16.61
GeMSS	17800.40	-	69223.60	-	142192.80
BlueGeMSS	2733.50	-	10449.80	-	17805.80
RedGeMSS	66.20	-	255.20	-	497.60
Luov Small Sig Chacha	-	39.80	-	98.20	176.20
Luov Small Sig Keccak	-	66.50	-	171.40	267.90
Luov Large Sig Chacha	-	207.40	-	568.00	1286.90
Luov Large Sig Keccak	-	222.60	-	623.10	1406.90
MQDSS	-	1219.10	-	3800.20	-
Picnic UR	137.10	-	365.90	-	673.10
Picnic FS	103.80	-	262.70	-	477.00
Picnic2 FS	3865.00	-	11413.50	-	24415.60
qTESLA	5.12	13.68	8.47	-	23.30
qTESLA-s	5.39	14.43	8.66	-	24.21
qTESLA-p	30.77	-	82.96	-	
qTESLA-size	-	-	-	-	31.30
qTESLA-size-s	-	-	-	-	33.17
Rainbow Classic	2.89	-	25.53	-	51.66
Rainbow Compressed/Cyclic	3.83	-	1902.70	-	4482.50
Rainbow Cyclic	3.22	-	24.75	-	54.97
SPHINCS+ SHA256 s simple	26494.90	-	63668.10	-	45710.80
SPHINCS+ SHA256 s robust	49013.50	-	120274.90	-	118541.20
SPHINCS+ SHA256 f simple	1799.70	-	2368.80	-	5236.80
SPHINCS+ SHA256 f robust	3446.70	-	4422.90	-	14426.20
SPHINCS+ SHAKE256 s simple	43964.30	-	86931.90	-	65658.40
SPHINCS+ SHAKE256 s robust	73310.80	-	148952.00	-	121794.40
SPHINCS+ SHAKE256 f simple	2926.10	-	3638.40	-	8049.60
SPHINCS+ SHAKE256 f robust	5257.30	-	6715.30	-	14767.70
SPHINCS+ HARAKA s simple	85968.10	184990.60	-	-	-
SPHINCS+ HARAKA s robust	130367.00	320977.50	-	-	-
SPHINCS+ HARAKA f simple	5367.00	6287.40	-	-	-
SPHINCS+ HARAKA f robust	8171.70	9742.30	-	-	-

Table 12: Energy consumption of `crypto_sign` function for **Signing** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	2.39	2.08	2.46	2.47	-
CRYSTALS-Dilithium AES	3.73	5.70	8.58	12.04	-
Falcon	1.41	-	-	-	2.73
GeMSS	1.70	-	4.10	-	8.29
BlueGeMSS	1.60	-	3.97	-	8.48
RedGeMSS	4.48	-	5.94	-	14.08
Luov Small Sig Chacha	-	31.70	-	78.70	138.20
Luov Small Sig Keccak	-	46.10	-	146.40	231.10
Luov Large Sig Chacha	-	134.00	-	370.80	653.10
Luov Large Sig Keccak	-	150.00	-	403.70	724.50
MQDSS	-	893.40	-	2825.10	-
Picnic UR	119.90	-	310.80	-	539.30
Picnic FS	97.90	-	227.60	-	416.40
Picnic2 FS	1853.80	-	4290.90	-	7862.40
qTESLA	1.23	2.85	2.12	-	4.37
qTESLA-s	1.15	2.90	2.34	-	4.43
qTESLA-p	6.94	-	19.46	-	-
qTESLA-size	-	-	-	-	6.20
qTESLA-size-s	-	-	-	-	6.07
Rainbow Classic	2.37	-	34.30	-	55.79
Rainbow Compressed/Cyclic	31.45	-	188.87	-	436.90
Rainbow Cyclic	31.62	-	183.00	-	460.50
SPHINCS+ SHA256 s simple	29.48	-	48.20	-	62.00
SPHINCS+ SHA256 s robust	59.13	-	99.37	-	185.20
SPHINCS+ SHA256 f simple	71.16	-	121.46	-	113.30
SPHINCS+ SHA256 f robust	151.26	-	237.49	-	353.40
SPHINCS+ SHAKE256 s simple	47.87	-	70.58	-	90.90
SPHINCS+ SHAKE256 s robust	92.77	-	132.04	-	179.60
SPHINCS+ SHAKE256 f simple	114.99	-	186.72	-	172.20
SPHINCS+ SHAKE256 f robust	221.60	-	346.07	-	376.60
SPHINCS+ HARAKA s simple	89.60	146.50	-	-	-
SPHINCS+ HARAKA s robust	136.80	231.50	-	-	-
SPHINCS+ HARAKA f simple	218.60	357.50	-	-	-
SPHINCS+ HARAKA f robust	355.10	533.90	-	-	-

Table 13: Energy consumption of `crypto_sign_open` function for **Verification** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	2.39	2.08	2.46	2.47	-
CRYSTALS-Dilithium AES	3.73	5.70	8.58	12.04	-
Falcon	1.41	-	-	-	2.73
GeMSS	1.70	-	4.10	-	8.29
BlueGeMSS	1.60	-	3.97	-	8.48
RedGeMSS	4.48	-	5.94	-	14.08
Luov Small Sig Chacha	-	31.70	-	78.70	138.20
Luov Small Sig Keccak	-	46.10	-	146.40	231.10
Luov Large Sig Chacha	-	134.00	-	370.80	653.10
Luov Large Sig Keccak	-	150.00	-	403.70	724.50
MQDSS	-	893.40	-	2825.10	-
Picnic UR	119.90	-	310.80	-	539.30
Picnic FS	97.90	-	227.60	-	416.40
Picnic2 FS	1853.80	-	4290.90	-	7862.40
qTESLA	1.23	2.85	2.12	-	4.37
qTESLA-s	1.15	2.90	2.34	-	4.43
qTESLA-p	6.94	-	19.46	-	-
qTESLA-size	-	-	-	-	6.20
qTESLA-size-s	-	-	-	-	6.07
Rainbow Classic	2.37	-	34.30	-	55.79
Rainbow Compressed/Cyclic	31.45	-	188.87	-	436.90
Rainbow Cyclic	31.62	-	183.00	-	460.50
SPHINCS+ SHA256 s simple	29.48	-	48.20	-	62.00
SPHINCS+ SHA256 s robust	59.13	-	99.37	-	185.20
SPHINCS+ SHA256 f simple	71.16	-	121.46	-	113.30
SPHINCS+ SHA256 f robust	151.26	-	237.49	-	353.40
SPHINCS+ SHAKE256 s simple	47.87	-	70.58	-	90.90
SPHINCS+ SHAKE256 s robust	92.77	-	132.04	-	179.60
SPHINCS+ SHAKE256 f simple	114.99	-	186.72	-	172.20
SPHINCS+ SHAKE256 f robust	221.60	-	346.07	-	376.60
SPHINCS+ HARAKA s simple	89.60	146.50	-	-	-
SPHINCS+ HARAKA s robust	136.80	231.50	-	-	-
SPHINCS+ HARAKA f simple	218.60	357.50	-	-	-
SPHINCS+ HARAKA f robust	355.10	533.90	-	-	-

Table 13: Energy consumption of **`crypto_sign_open`** function for **Verification** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Results for Assembly Optimized Implementation

Key Encapsulation Mechanisms

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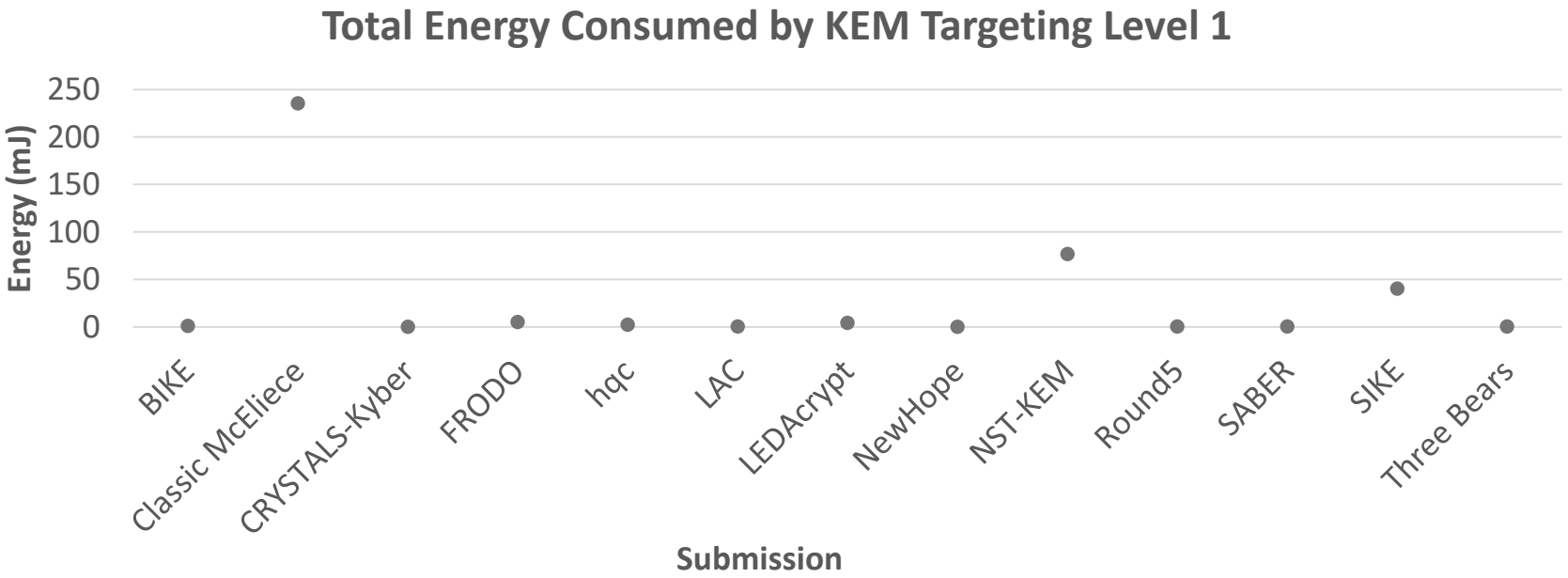
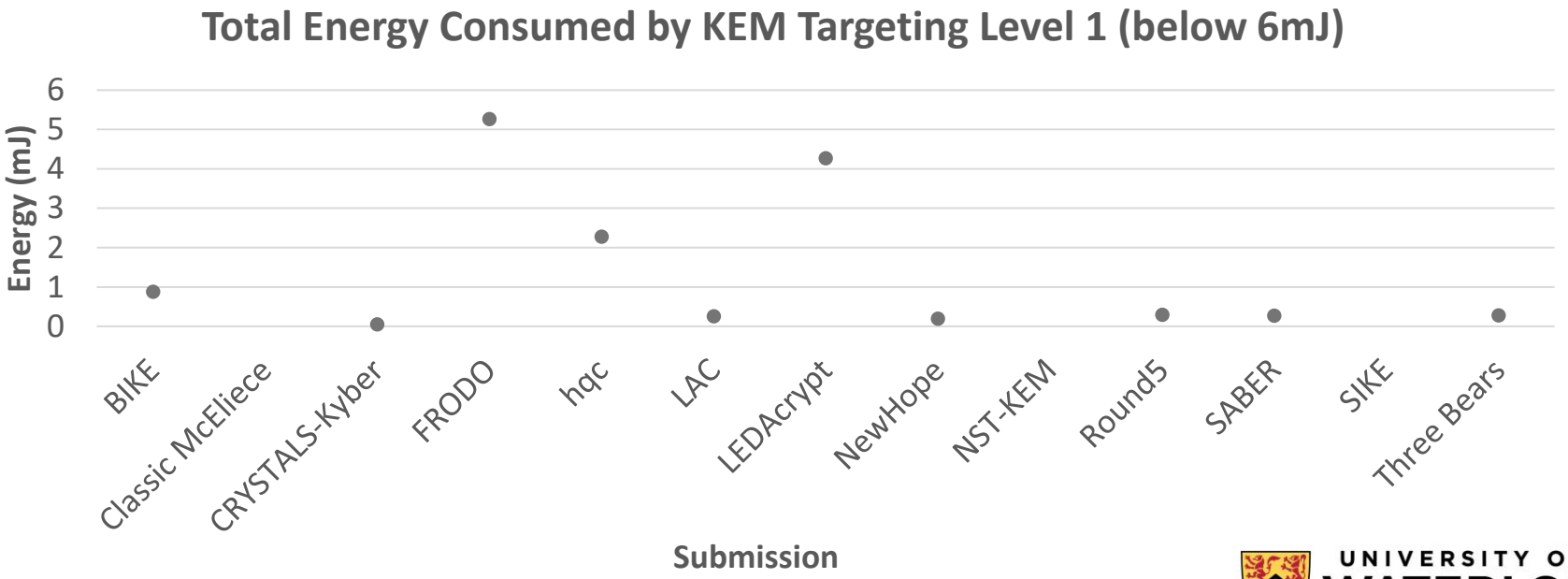

Total Energy Consumed by KEM Targeting Level 1
Energy (mJ)
250
200
150
100
50
0
BIKE
Classic McEliece
CRYSTALS-Kyber
FRODO
hqc
LAC
LEDAcrypt
NewHope
NST-KEM
Round5
SABER
SIKE
Three Bears
Submission


Total Energy Consumed by KEM Targeting Level 1 (below 6mJ)
Energy (mJ)
6
5
4
3
2
1
0
BIKE
Classic McEliece
CRYSTALS-Kyber
FRODO
hqc
LAC
LEDAcrypt
NewHope
NST-KEM
Round5
SABER
SIKE
Three Bears
Submission

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE1	0.304	-	0.922	-	2.138
BIKE2	22.535	-	82.097	-	230.485
BIKE3	0.185	-	0.591	-	1.375
Classic McEliece AVX	234.940	-	857.444	-	1659.074
Classic McEliece SSE	463.182	-	1507.966	-	2274.669
CRYSTALS-Kyber	0.021	-	0.083	-	0.117
CRYSTALS-Kyber-90s	0.014	-	0.018	-	0.026
FRODO AES	1.582	-	2.981	-	3.481
FRODO SHAKE	6.121	-	12.927	-	22.985
hqc-1	0.317	-	0.599	-	0.955
hqc-2	-	-	0.649	-	0.964
hqc-3	-	-	-	-	1.009
LAC	0.064	-	0.112	-	0.145
LEDAcrypt N02	5.756	-	17.681	-	36.900
LEDAcrypt N03	2.501	-	8.418	-	22.711
LEDAcrypt N04	4.135	-	11.942	-	24.722
LEDAcrypt DFR64	1417.029	-	4680.601	-	14371.200
LEDAcrypt DFRSL	2087.827	-	7311.765	-	20787.330
NewHope CCA	0.094	-	-	-	0.178
NewHope CPA	0.068	-	-	-	0.145
NTRU-HRSS	-	-	0.325	-	-
NTS-KEM AVX	75.823	-	242.256	-	434.092
NTS-KEM SSE	79.173	-	241.025	-	443.702
Round5 Ring	0.078	-	0.282	-	0.360
Round5 Ring 5	0.113	-	0.187	-	0.331
Round5 Non-Ring	0.846	-	1.522	-	3.753
Round 5 LongKey	0.143	-	-	-	-
SABER	0.064	-	0.139	-	0.198
SIKE	9.287	13.075	22.065	-	37.085
SIKE Compressed	24.768	33.980	58.277	-	90.272
Three Bears	-	0.097	-	0.180	0.292
Three Bears Eph.	-	0.098	-	0.189	0.295

Table 14: Energy consumption of **`crypto_kem_keypair`** function for **Keypair Generation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE1	0.304	-	0.922	-	2.138
BIKE2	22.535	-	82.097	-	230.485
BIKE3	0.185	-	0.591	-	1.375
Classic McEliece AVX	234.940	-	857.444	-	1659.074
Classic McEliece SSE	463.182	-	1507.966	-	2274.669
CRYSTALS-Kyber	0.021	-	0.083	-	0.117
CRYSTALS-Kyber-90s	0.014	-	0.018	-	0.026
FRODO AES	1.582	-	2.981	-	3.481
FRODO SHAKE	6.121	-	12.927	-	22.985
hqc-1	0.317	-	0.599	-	0.955
hqc-2	-	-	0.649	-	0.964
hqc-3	-	-	-	-	1.009
LAC	0.064	-	0.112	-	0.145
LEDAcrypt N02	5.756	-	17.681	-	36.900
LEDAcrypt N03	2.501	-	8.418	-	22.711
LEDAcrypt N04	4.135	-	11.942	-	24.722
LEDAcrypt DFR64	1417.029	-	4680.601	-	14371.200
LEDAcrypt DFRSL	2087.827	-	7311.765	-	20787.330
NewHope CCA	0.094	-	-	-	0.178
NewHope CPA	0.068	-	-	-	0.145
NTRU-HRSS	-	-	0.325	-	-
NTS-KEM AVX	75.823	-	242.256	-	434.092
NTS-KEM SSE	79.173	-	241.025	-	443.702
Round5 Ring	0.078	-	0.282	-	0.360
Round5 Ring 5	0.113	-	0.187	-	0.331
Round5 Non-Ring	0.846	-	1.522	-	3.753
Round 5 LongKey	0.143	-	-	-	-
SABER	0.064	-	0.139	-	0.198
SIKE	9.287	13.075	22.065	-	37.085
SIKE Compressed	24.768	33.980	58.277	-	90.272
Three Bears	-	0.097	-	0.180	0.292
Three Bears Eph.	-	0.098	-	0.189	0.295

Table 14: Energy consumption of **`crypto_kem_keypair`** function for **Keypair Generation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE1	0.358	-	1.046	-	2.368
BIKE2	0.187	-	0.442	-	1.135
BIKE3	0.337	-	1.130	-	2.790
Classic McEliece AVX	0.059	-	0.111	-	0.087
Classic McEliece SSE	0.062	-	0.114	-	0.143
CRYSTALS-Kyber	0.090	-	0.108	-	0.145
CRYSTALS-Kyber-90s	0.018	-	0.020	-	0.039
FRODO AES	1.917	-	3.474	-	5.279
FRODO SHAKE	6.687	-	14.067	-	24.482
hqc-1	0.647	-	1.160	-	1.734
hqc-2	-	-	1.227	-	1.899
hqc-3	-	-	-	-	2.004
LAC	0.087	-	0.146	-	0.244
LEDAcrypt N02	0.223	-	0.469	-	0.856
LEDAcrypt N03	0.164	-	0.381	-	0.865
LEDAcrypt N04	0.188	-	0.528	-	1.004
LEDAcrypt DFR64	0.675	-	1.296	-	2.830
LEDAcrypt DFRSL	0.803	-	2.770	-	4.230
NewHope CCA	0.137	-	-	-	0.251
NewHope CPA	0.102	-	-	-	0.194
NTRU-HRSS	-	-	0.131	-	-
NTS-KEM AVX	0.161	-	0.682	-	0.932
NTS-KEM SSE	0.164	-	0.683	-	0.941
Round5 Ring	0.145	-	0.470	-	0.606
Round5 Ring 5	0.194	-	0.342	-	0.548
Round5 Non-Ring	0.913	-	1.631	-	3.795
Round 5 LongKey	0.191	-	-	-	-
SABER	0.110	-	0.166	-	0.234
SIKE	15.006	21.113	40.641	-	60.455
SIKE Compressed	29.527	39.560	69.651	-	114.244
Three Bears	-	0.135	-	0.210	0.339
Three Bears Eph.	-	0.126	-	0.210	0.342

Table 15: Energy consumption of **`crypto_kem_enc`** function for **Encapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE1	0.358	-	1.046	-	2.368
BIKE2	0.187	-	0.442	-	1.135
BIKE3	0.337	-	1.130	-	2.790
Classic McEliece AVX	0.059	-	0.111	-	0.087
Classic McEliece SSE	0.062	-	0.114	-	0.143
CRYSTALS-Kyber	0.090	-	0.108	-	0.145
CRYSTALS-Kyber-90s	0.018	-	0.020	-	0.039
FRODO AES	1.917	-	3.474	-	5.279
FRODO SHAKE	6.687	-	14.067	-	24.482
hqc-1	0.647	-	1.160	-	1.734
hqc-2	-	-	1.227	-	1.899
hqc-3	-	-	-	-	2.004
LAC	0.087	-	0.146	-	0.244
LEDAcrypt N02	0.223	-	0.469	-	0.856
LEDAcrypt N03	0.164	-	0.381	-	0.865
LEDAcrypt N04	0.188	-	0.528	-	1.004
LEDAcrypt DFR64	0.675	-	1.296	-	2.830
LEDAcrypt DFRSL	0.803	-	2.770	-	4.230
NewHope CCA	0.137	-	-	-	0.251
NewHope CPA	0.102	-	-	-	0.194
NTRU-HRSS	-	-	0.131	-	-
NTS-KEM AVX	0.161	-	0.682	-	0.932
NTS-KEM SSE	0.164	-	0.683	-	0.941
Round5 Ring	0.145	-	0.470	-	0.606
Round5 Ring 5	0.194	-	0.342	-	0.548
Round5 Non-Ring	0.913	-	1.631	-	3.795
Round 5 LongKey	0.191	-	-	-	-
SABER	0.110	-	0.166	-	0.234
SIKE	15.006	21.113	40.641	-	60.455
SIKE Compressed	29.527	39.560	69.651	-	114.244
Three Bears	-	0.135	-	0.210	0.339
Three Bears Eph.	-	0.126	-	0.210	0.342

Table 15: Energy consumption of **`crypto_kem_enc`** function for **Encapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE1	0.457	-	1.152	-	2.660
BIKE2	0.254	-	0.726	-	1.489
BIKE3	0.354	-	0.887	-	2.099
Classic McEliece AVX	0.190	-	0.179	-	0.264
Classic McEliece SSE	0.160	-	0.201	-	0.162
CRYSTALS-Kyber	0.047	-	0.081	-	0.135
CRYSTALS-Kyber-90s	0.014	-	0.028	-	0.043
FRODO AES	1.763	-	3.086	-	4.975
FRODO SHAKE	6.515	-	13.629	-	24.725
hqc-1	1.310	-	2.018	-	3.012
hqc-2	-	-	2.189	-	3.195
hqc-3	-	-	-	-	3.310
LAC	0.103	-	0.263	-	0.320
LEDAcrypt N02	1.254	-	3.137	-	5.973
LEDAcrypt N03	1.596	-	3.764	-	7.140
LEDAcrypt N04	4.203	-	9.427	-	15.056
LEDAcrypt DFR64	1.598	-	3.655	-	6.450
LEDAcrypt DFRSL	2.265	-	5.064	-	9.380
NewHope CCA	0.146	-	-	-	0.253
NewHope CPA	0.022	-	-	-	0.034
NTRU-HRSS	-	-	0.053	-	-
NTS-KEM AVX	0.805	-	1.471	-	2.611
NTS-KEM SSE	1.337	-	2.413	-	4.707
Round5 Ring	0.066	-	0.256	-	0.321
Round5 Ring 5	0.088	-	0.168	-	0.290
Round5 Non-Ring	0.378	-	0.515	-	1.969
Round 5 LongKey	0.061	-	-	-	-
SABER	0.092	-	0.156	-	0.249
SIKE	15.823	22.772	40.642	-	65.121
SIKE Compressed	27.293	37.180	66.586	-	104.814
Three Bears	-	0.192	-	0.316	0.461
Three Bears Eph.	-	0.051	-	0.070	0.076

Table 16: Energy consumption of **`crypto_kem_dec`** function for **Decapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
BIKE1	0.457	-	1.152	-	2.660
BIKE2	0.254	-	0.726	-	1.489
BIKE3	0.354	-	0.887	-	2.099
Classic McEliece AVX	0.190	-	0.179	-	0.264
Classic McEliece SSE	0.160	-	0.201	-	0.162
CRYSTALS-Kyber	0.047	-	0.081	-	0.135
CRYSTALS-Kyber-90s	0.014	-	0.028	-	0.043
FRODO AES	1.763	-	3.086	-	4.975
FRODO SHAKE	6.515	-	13.629	-	24.725
hqc-1	1.310	-	2.018	-	3.012
hqc-2	-	-	2.189	-	3.195
hqc-3	-	-	-	-	3.310
LAC	0.103	-	0.263	-	0.320
LEDAcrypt N02	1.254	-	3.137	-	5.973
LEDAcrypt N03	1.596	-	3.764	-	7.140
LEDAcrypt N04	4.203	-	9.427	-	15.056
LEDAcrypt DFR64	1.598	-	3.655	-	6.450
LEDAcrypt DFRSL	2.265	-	5.064	-	9.380
NewHope CCA	0.146	-	-	-	0.253
NewHope CPA	0.022	-	-	-	0.034
NTRU-HRSS	-	-	0.053	-	-
NTS-KEM AVX	0.805	-	1.471	-	2.611
NTS-KEM SSE	1.337	-	2.413	-	4.707
Round5 Ring	0.066	-	0.256	-	0.321
Round5 Ring 5	0.088	-	0.168	-	0.290
Round5 Non-Ring	0.378	-	0.515	-	1.969
Round 5 LongKey	0.061	-	-	-	-
SABER	0.092	-	0.156	-	0.249
SIKE	15.823	22.772	40.642	-	65.121
SIKE Compressed	27.293	37.180	66.586	-	104.814
Three Bears	-	0.192	-	0.316	0.461
Three Bears Eph.	-	0.051	-	0.070	0.076

Table 16: Energy consumption of **`crypto_kem_dec`** function for **Decapsulation** of Round 2 **Key Encapsulation Mechanisms**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

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Results for Assembly Optimized Implementation

Public-Key Encryption Schemes

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Table 17: Energy consumption of **`crypto_encrypt_keypair`** function for **Keypair Generation** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	1420.300	4751.320	14271.160
LEDAcrypt DFRSL	1961.020	7322.090	21125.400
LAC	0.098	0.311	0.268

Table 18: Energy consumption of **`crypto_encrypt`** function for **Encryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	1.410	2.520	4.540
LEDAcrypt DFRSL	1.930	4.600	7.280
LAC	0.176	0.296	0.482

Table 19: Energy consumption of **`crypto_encrypt_open`** function for **Decryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	3.550	6.660	11.740
LEDAcrypt DFRSL	4.890	10.040	18.000
LAC	0.080	0.183	0.208

Table 17: Energy consumption of **`crypto_encrypt_keypair`** function for **Keypair Generation** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	1420.300	4751.320	14271.160
LEDAcrypt DFRSL	1961.020	7322.090	21125.400
LAC	0.098	0.311	0.268

Table 18: Energy consumption of **`crypto_encrypt`** function for **Encryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	1.410	2.520	4.540
LEDAcrypt DFRSL	1.930	4.600	7.280
LAC	0.176	0.296	0.482

Highest energy per level

Lowest energy per level

Table 19: Energy consumption of **`crypto_encrypt_open`** function for **Decryption** of Round 2 **Public-key Encryption** schemes. Energy is in milliJoules.

	Level 1	Level 3	Level 5
LEDAcrypt DFR64	3.550	6.660	11.740
LEDAcrypt DFRSL	4.890	10.040	18.000
LAC	0.080	0.183	0.208

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Results for Assembly Optimized Implementation

Digital Signature Schemes

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Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	0.118	0.167	0.255	0.369	-
CRYSTALS-Dilithium AES	0.100	0.115	0.168	0.233	-
GeMSS	65.017	-	329.908	-	1017.190
BlueGeMSS	65.691	-	327.297	-	997.568
RedGeMSS	76.858	-	339.969	-	1009.862
Luov Small Sig Chacha	-	2.790	-	12.941	21.611
Luov Small Sig Keccak	-	5.171	-	17.652	29.943
MQDSS	-	1.096	-	2.582	-
Picnic UR	0.049	-	0.061	-	0.068
Picnic FS	0.026	-	0.058	-	0.079
Picnic2 FS	0.052	-	0.066	-	0.074
qTESLA	1.464	-	4.376	-	21.869
qTESLA-s	1.524	-	4.124	-	21.532
Rainbow Classic	13.084	-	121.867	-	184.880
Rainbow Compressed/Cyclic	14.087	-	136.343	-	200.194
Rainbow Cyclic	14.176	-	138.416	-	198.908
Rainbow SSE Classic	14.066	-	123.136	-	202.550
Rainbow SSE Compressed/Cyclic	14.680	-	141.406	-	223.691
Rainbow SSE Cyclic	14.904	-	143.365	-	221.944
SPHINCS+ SHA256 s simple	615.820	-	86.960	-	111.380
SPHINCS+ SHA256 s robust	1125.340	-	1650.120	-	445.310
SPHINCS+ SHA256 f simple	19.760	-	29.080	-	7.090
SPHINCS+ SHA256 f robust	39.150	-	54.190	-	28.730
SPHINCS+ SHAKE256 s simple	188.190	-	270.230	-	373.390
SPHINCS+ SHAKE256 s robust	362.230	-	522.330	-	691.150
SPHINCS+ SHAKE256 f simple	6.070	-	9.040	-	23.140
SPHINCS+ SHAKE256 f robust	11.610	-	16.160	-	43.230
SPHINCS+ HARAKA s simple	157.070	263.720	-	-	-
SPHINCS+ HARAKA s robust	252.400	364.310	-	-	-
SPHINCS+ HARAKA f simple	7.010	10.010	-	-	-
SPHINCS+ HARAKA f robust	10.760	13.310	-	-	-

Table 20: Energy consumption of **`crypto_sign_keypair`** function for **Keypair Generation** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	0.118	0.167	0.255	0.369	-
CRYSTALS-Dilithium AES	0.100	0.115	0.168	0.233	-
GeMSS	65.017	-	329.908	-	1017.190
BlueGeMSS	65.691	-	327.297	-	997.568
RedGeMSS	76.858	-	339.969	-	1009.862
Luov Small Sig Chacha	-	2.790	-	12.941	21.611
Luov Small Sig Keccak	-	5.171	-	17.652	29.943
MQDSS	-	1.096	-	2.582	-
Picnic UR	0.049	-	0.061	-	0.068
Picnic FS	0.026	-	0.058	-	0.079
Picnic2 FS	0.052	-	0.066	-	0.074
qTESLA	1.464	-	4.376	-	21.869
qTESLA-s	1.524	-	4.124	-	21.532
Rainbow Classic	13.084	-	121.867	-	184.880
Rainbow Compressed/Cyclic	14.087	-	136.343	-	200.194
Rainbow Cyclic	14.176	-	138.416	-	198.908
Rainbow SSE Classic	14.066	-	123.136	-	202.550
Rainbow SSE Compressed/Cyclic	14.680	-	141.406	-	223.691
Rainbow SSE Cyclic	14.904	-	143.365	-	221.944
SPHINCS+ SHA256 s simple	615.820	-	86.960	-	111.380
SPHINCS+ SHA256 s robust	1125.340	-	1650.120	-	445.310
SPHINCS+ SHA256 f simple	19.760	-	29.080	-	7.090
SPHINCS+ SHA256 f robust	39.150	-	54.190	-	28.730
SPHINCS+ SHAKE256 s simple	188.190	-	270.230	-	373.390
SPHINCS+ SHAKE256 s robust	362.230	-	522.330	-	691.150
SPHINCS+ SHAKE256 f simple	6.070	-	9.040	-	23.140
SPHINCS+ SHAKE256 f robust	11.610	-	16.160	-	43.230
SPHINCS+ HARAKA s simple	157.070	263.720	-	-	-
SPHINCS+ HARAKA s robust	252.400	364.310	-	-	-
SPHINCS+ HARAKA f simple	7.010	10.010	-	-	-
SPHINCS+ HARAKA f robust	10.760	13.310	-	-	-

Table 20: Energy consumption of **`crypto_sign_keypair`** function for **Keypair Generation** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	0.392	0.611	0.687	0.729	-
CRYSTALS-Dilithium AES	0.244	0.443	0.588	0.605	-
GeMSS	1244.551	-	3391.091	-	5751.300
BlueGeMSS	196.217	-	502.963	-	791.175
RedGeMSS	7.240	-	18.016	-	27.660
Luov Small Sig Chacha	-	1.258	-	3.238	5.370
Luov Small Sig Keccak	-	3.619	-	8.182	13.645
MQDSS	-	4.543	-	11.769	-
Picnic UR	19.670	-	48.329	-	79.814
Picnic FS	14.801	-	35.907	-	60.796
Picnic2 FS	486.873	-	1388.546	-	2764.521
qTESLA	0.388	-	0.478	-	1.038
qTESLA-s	0.414	-	0.482	-	1.099
Rainbow Classic	0.087	-	0.781	-	1.052
Rainbow Compressed/Cyclic	9.404	-	85.453	-	134.780
Rainbow Cyclic	0.107	-	0.800	-	1.032
Rainbow SSE Classic	0.208	-	0.824	-	1.191
Rainbow SSE Compressed/Cyclic	9.602	-	87.802	-	144.781
Rainbow SSE Cyclic	0.204	-	0.822	-	1.177
SPHINCS+ SHA256 s simple	10883.230	-	2310.780	-	1460.860
SPHINCS+ SHA256 s robust	21286.640	-	40865.710	-	5457.770
SPHINCS+ SHA256 f simple	649.140	-	872.450	-	175.980
SPHINCS+ SHA256 f robust	1269.120	-	1714.890	-	673.160
SPHINCS+ SHAKE256 s simple	3043.750	-	6489.690	-	4596.470
SPHINCS+ SHAKE256 s robust	5473.480	-	11314.230	-	8200.250
SPHINCS+ SHAKE256 f simple	193.970	-	257.790	-	551.490
SPHINCS+ SHAKE256 f robust	351.300	-	475.700	-	1004.150
SPHINCS+ HARAKA s simple	3474.440	7529.410	-	-	-
SPHINCS+ HARAKA s robust	4673.460	11891.060	-	-	-
SPHINCS+ HARAKA f simple	152.790	231.180	-	-	-
SPHINCS+ HARAKA f robust	260.930	329.050	-	-	-

Table 21: Energy consumption of `crypto_sign` function for **Signing** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	0.392	0.611	0.687	0.729	-
CRYSTALS-Dilithium AES	0.244	0.443	0.588	0.605	-
GeMSS	1244.551	-	3391.091	-	5751.300
BlueGeMSS	196.217	-	502.963	-	791.175
RedGeMSS	7.240	-	18.016	-	27.660
Luov Small Sig Chacha	-	1.258	-	3.238	5.370
Luov Small Sig Keccak	-	3.619	-	8.182	13.645
MQDSS	-	4.543	-	11.769	-
Picnic UR	19.670	-	48.329	-	79.814
Picnic FS	14.801	-	35.907	-	60.796
Picnic2 FS	486.873	-	1388.546	-	2764.521
qTESLA	0.388	-	0.478	-	1.038
qTESLA-s	0.414	-	0.482	-	1.099
Rainbow Classic	0.087	-	0.781	-	1.052
Rainbow Compressed/Cyclic	9.404	-	85.453	-	134.780
Rainbow Cyclic	0.107	-	0.800	-	1.032
Rainbow SSE Classic	0.208	-	0.824	-	1.191
Rainbow SSE Compressed/Cyclic	9.602	-	87.802	-	144.781
Rainbow SSE Cyclic	0.204	-	0.822	-	1.177
SPHINCS+ SHA256 s simple	10883.230	-	2310.780	-	1460.860
SPHINCS+ SHA256 s robust	21286.640	-	40865.710	-	5457.770
SPHINCS+ SHA256 f simple	649.140	-	872.450	-	175.980
SPHINCS+ SHA256 f robust	1269.120	-	1714.890	-	673.160
SPHINCS+ SHAKE256 s simple	3043.750	-	6489.690	-	4596.470
SPHINCS+ SHAKE256 s robust	5473.480	-	11314.230	-	8200.250
SPHINCS+ SHAKE256 f simple	193.970	-	257.790	-	551.490
SPHINCS+ SHAKE256 f robust	351.300	-	475.700	-	1004.150
SPHINCS+ HARAKA s simple	3474.440	7529.410	-	-	-
SPHINCS+ HARAKA s robust	4673.460	11891.060	-	-	-
SPHINCS+ HARAKA f simple	152.790	231.180	-	-	-
SPHINCS+ HARAKA f robust	260.930	329.050	-	-	-

Table 21: Energy consumption of `crypto_sign` function for **Signing** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	0.169	0.222	0.294	0.372	-
CRYSTALS-Dilithium AES	0.137	0.167	0.184	0.254	-
GeMSS	0.331	-	0.719	-	2.080
BlueGeMSS	0.321	-	0.758	-	1.575
RedGeMSS	0.585	-	1.241	-	2.410
Luov Small Sig Chacha	-	0.333	-	1.156	1.501
Luov Small Sig Keccak	-	2.697	-	6.070	9.731
MQDSS	-	3.096	-	8.084	-
Picnic UR	15.763	-	39.132	-	65.796
Picnic FS	11.962	-	29.856	-	51.307
Picnic2 FS	261.616	-	603.427	-	1060.452
qTESLA	0.145	-	0.266	-	0.401
qTESLA-s	0.130	-	0.228	-	0.419
Rainbow Classic	0.031	-	0.161	-	0.274
Rainbow Compressed/Cyclic	5.539	-	29.937	-	72.646
Rainbow Cyclic	5.449	-	30.165	-	73.366
Rainbow SSE Classic	0.099	-	0.890	-	0.796
Rainbow SSE Compressed/Cyclic	5.484	-	30.973	-	73.050
Rainbow SSE Cyclic	5.607	-	31.252	-	73.067
SPHINCS+ SHA256 s simple	29.760	-	4.630	-	6.030
SPHINCS+ SHA256 s robust	60.540	-	95.520	-	18.150
SPHINCS+ SHA256 f simple	69.880	-	114.380	-	12.280
SPHINCS+ SHA256 f robust	146.300	-	238.020	-	35.630
SPHINCS+ SHAKE256 s simple	5.190	-	7.490	-	10.000
SPHINCS+ SHAKE256 s robust	9.890	-	14.070	-	19.020
SPHINCS+ SHAKE256 f simple	11.830	-	18.970	-	20.010
SPHINCS+ SHAKE256 f robust	22.480	-	36.420	-	38.920
SPHINCS+ HARAKA s simple	4.130	5.390	-	-	-
SPHINCS+ HARAKA s robust	7.200	11.910	-	-	-
SPHINCS+ HARAKA f simple	8.710	13.440	-	-	-
SPHINCS+ HARAKA f robust	16.340	28.980	-	-	-

Table 22: Energy consumption of **`crypto_sign_open`** function for **Verification** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Scheme \ Security Level	Level 1	Level 2	Level 3	Level 4	Level 5
CRYSTALS-Dilithium SHAKE	0.169	0.222	0.294	0.372	-
CRYSTALS-Dilithium AES	0.137	0.167	0.184	0.254	-
GeMSS	0.331	-	0.719	-	2.080
BlueGeMSS	0.321	-	0.758	-	1.575
RedGeMSS	0.585	-	1.241	-	2.410
Luov Small Sig Chacha	-	0.333	-	1.156	1.501
Luov Small Sig Keccak	-	2.697	-	6.070	9.731
MQDSS	-	3.096	-	8.084	-
Picnic UR	15.763	-	39.132	-	65.796
Picnic FS	11.962	-	29.856	-	51.307
Picnic2 FS	261.616	-	603.427	-	1060.452
qTESLA	0.145	-	0.266	-	0.401
qTESLA-s	0.130	-	0.228	-	0.419
Rainbow Classic	0.031	-	0.161	-	0.274
Rainbow Compressed/Cyclic	5.539	-	29.937	-	72.646
Rainbow Cyclic	5.449	-	30.165	-	73.366
Rainbow SSE Classic	0.099	-	0.890	-	0.796
Rainbow SSE Compressed/Cyclic	5.484	-	30.973	-	73.050
Rainbow SSE Cyclic	5.607	-	31.252	-	73.067
SPHINCS+ SHA256 s simple	29.760	-	4.630	-	6.030
SPHINCS+ SHA256 s robust	60.540	-	95.520	-	18.150
SPHINCS+ SHA256 f simple	69.880	-	114.380	-	12.280
SPHINCS+ SHA256 f robust	146.300	-	238.020	-	35.630
SPHINCS+ SHAKE256 s simple	5.190	-	7.490	-	10.000
SPHINCS+ SHAKE256 s robust	9.890	-	14.070	-	19.020
SPHINCS+ SHAKE256 f simple	11.830	-	18.970	-	20.010
SPHINCS+ SHAKE256 f robust	22.480	-	36.420	-	38.920
SPHINCS+ HARAKA s simple	4.130	5.390	-	-	-
SPHINCS+ HARAKA s robust	7.200	11.910	-	-	-
SPHINCS+ HARAKA f simple	8.710	13.440	-	-	-
SPHINCS+ HARAKA f robust	16.340	28.980	-	-	-

Table 22: Energy consumption of **`crypto_sign_open`** function for **Verification** of Round 2 **Digital Signatures**. Energy is in milliJoules.

Highest energy per level

Lowest energy per level

Discussion of Results

- Using the energy consumption results shown in the previous section, the candidate submissions are ranked
- In this ranking, we do not consider the different variants of each algorithm, but rather the best energy consuming variant in each submission package to best compare each proposed algorithm against each other
- To provide a comprehensive comparison, the results from levels 2 and 4 are consolidated into the results from 1 and 3, respectively
- For rankings of Assembly Optimized Implementation, a reference to its rank in the Optimized C Implementation is provided for ease of comparison

Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	Round5	Round5	Round5
2	Three Bears	Three Bears	Three Bears
3	LAC	SABER	LAC
4	SABER	LAC	SABER
5	BIKE	ROLLO	ROLLO
Rank	**Encapsulation**		
1	NTS-KEM	Three Bears	Three Bears
2	Three Bears	Round5	Round5
3	Round5	Classic McEliece	LAC
4	LAC	LAC	NTS-KEM
5	Classic McEliece	NTS-KEM	Classic McEliece
Rank	**Decapsulation**		
1	Round5	Three Bears	Three Bears
2	Three Bears	Round5	Round5
3	NewHope	LAC	NewHope
4	LAC	CRYSTALS-Kyber	LAC
5	NTS-KEM	NTS-KEM	CRYSTALS-Kyber

Table 23: The top five most energy efficient submissions for functions pertaining to **Key Encapsulation Mechanisms**. Results are from **Optimized C Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3.

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Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	Round5	Round5	Round5
2	Three Bears	Three Bears	Three Bears
3	LAC	SABER	LAC
4	SABER	LAC	SABER
5	BIKE	ROLLO	ROLLO
Rank	**Encapsulation**		
1	NTS-KEM	Three Bears	Three Bears
2	Three Bears	Round5	Round5
3	Round5	Classic McEliece	LAC
4	LAC	LAC	NTS-KEM
5	Classic McEliece	NTS-KEM	Classic McEliece
Rank	**Decapsulation**		
1	Round5	Three Bears	Three Bears
2	Three Bears	Round5	Round5
3	NewHope	LAC	NewHope
4	LAC	CRYSTALS-Kyber	LAC
5	NTS-KEM	NTS-KEM	CRYSTALS-Kyber

Table 23: The top five most energy efficient submissions for functions pertaining to **Key Encapsulation Mechanisms**. Results are from **Optimized C Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3.

Lattice-based

Code-based

Other

Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	CRYSTALS-Kyber (7)	CRYSTALS-Kyber (6)	CRYSTALS-Kyber (7)
2	LAC (3)	LAC (4)	LAC (3)
3	SABER (4)	SABER (3)	NewHope (6)
4	NewHope (8)	Three Bears (2)	SABER (4)
5	Round5 (1)	Round5 (1)	Three Bears (2)
Rank	**Encapsulation**		
1	CRYSTALS-Kyber (8)	CRYSTALS-Kyber (8)	CRYSTALS-Kyber (9)
2	Classic McEliece (5)	Classic McEliece (3)	Classic McEliece (5)
3	LAC (4)	NTRU (12)	NewHope (8)
4	NewHope (9)	LAC (4)	SABER (11)
5	SABER (14)	SABER (10)	LAC (3)
Rank	**Decapsulation**		
1	CRYSTALS-Kyber (4)	CRYSTALS-Kyber (4)	NewHope (3)
2	NewHope (3)	NTRU (11)	CRYSTALS-Kyber (5)
3	Three Bears (2)	Three Bears (1)	Three Bears (1)
4	Round5 (1)	SABER (8)	Classic McEliece (14)
5	LAC (4)	Round5 (2)	SABER (9)

Table 24: The top five most energy efficient submissions for functions pertaining to **Key Encapsulation Mechanisms**. Results are from **Assembly Optimized Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3. Brackets indicate rank in portable C implementation.

Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	CRYSTALS-Kyber (7)	CRYSTALS-Kyber (6)	CRYSTALS-Kyber (7)
2	LAC (3)	LAC (4)	LAC (3)
3	SABER (4)	SABER (3)	NewHope (6)
4	NewHope (8)	Three Bears (2)	SABER (4)
5	Round5 (1)	Round5 (1)	Three Bears (2)
Rank	**Encapsulation**		
1	CRYSTALS-Kyber (8)	CRYSTALS-Kyber (8)	CRYSTALS-Kyber (9)
2	Classic McEliece (5)	Classic McEliece (3)	Classic McEliece (5)
3	LAC (4)	NTRU (12)	NewHope (8)
4	NewHope (9)	LAC (4)	SABER (11)
5	SABER (14)	SABER (10)	LAC (3)
Rank	**Decapsulation**		
1	CRYSTALS-Kyber (4)	CRYSTALS-Kyber (4)	NewHope (3)
2	NewHope (3)	NTRU (11)	CRYSTALS-Kyber (5)
3	Three Bears (2)	Three Bears (1)	Three Bears (1)
4	Round5 (1)	SABER (8)	Classic McEliece (14)
5	LAC (4)	Round5 (2)	SABER (9)

Table 24: The top five most energy efficient submissions for functions pertaining to **Key Encapsulation Mechanisms**. Results are from **Assembly Optimized Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3. Brackets indicate rank in portable C implementation.

Lattice-based

Code-based

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Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Total**		
1	Round5	Three Bears	Three Bears
2	Three Bears	Round5	Round5
3	LAC	LAC	LAC
4	NewHope	CRYSTALS-Kyber	ROLLO
5	CRYSTALS-Kyber	ROLLO	NewHope

Table 25: The top five most energy efficient submissions for **total** energy consumed of **Key Encapsulation Mechanisms**. Results are from **Optimized C Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3.

Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Total**		
1	Round5	Three Bears	Three Bears
2	Three Bears	Round5	Round5
3	LAC	LAC	LAC
4	NewHope	CRYSTALS-Kyber	ROLLO
5	CRYSTALS-Kyber	ROLLO	NewHope

Table 25: The top five most energy efficient submissions for **total** energy consumed of **Key Encapsulation Mechanisms**. Results are from **Optimized C Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3.

Lattice-based

Other

Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Total**		
1	CRYSTALS-Kyber (5)	CRYSTALS-Kyber (4)	CRYSTALS-Kyber (5)
2	NewHope (4)	SABER (6)	NewHope (4)
3	LAC (3)	Three Bears (1)	SABER (7)
4	SABER (8)	NTRU (14)	LAC (3)
5	Three Bears (2)	LAC (3)	Three Bears (1)

Table 26: The top five most energy efficient submissions for **total** energy consumed of **Key Encapsulation Mechanisms**. Results are from **Assembly Optimized Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3. Brackets indicate rank in portable C implementation.

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Analysis of Key Encapsulation Mechanisms

	Level 1	Level 3	Level 5
Rank	**Total**		
1	CRYSTALS-Kyber (5)	CRYSTALS-Kyber (4)	CRYSTALS-Kyber (5)
2	NewHope (4)	SABER (6)	NewHope (4)
3	LAC (3)	Three Bears (1)	SABER (7)
4	SABER (8)	NTRU (14)	LAC (3)
5	Three Bears (2)	LAC (3)	Three Bears (1)

Table 26: The top five most energy efficient submissions for **total** energy consumed of **Key Encapsulation Mechanisms**. Results are from **Assembly Optimized Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3. Brackets indicate rank in portable C implementation.

Lattice-based

Analysis of Digital Signatures

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	Picnic	Picnic	Picnic
2	CRYSTALS-Dilithium	CRYSTALS-Dilithium	qTESLA
3	qTESLA	qTESLA	SPHINCS+
4	MQDSS	MQDSS	Luov
5	SPHINCS+	SPHINCS+	Falcon
Rank	**Signing**		
1	Rainbow	CRYSTALS-Dilithium	Falcon
2	qTESLA	qTESLA	qTESLA
3	Falcon	Rainbow	Rainbow
4	CRYSTALS-Dilithium	Luov	Luov
5	Luov	GeMSS	Picnic
Rank	**Verification**		
1	qTESLA	qTESLA	Falcon
2	Falcon	CRYSTALS-Dilithium	qTESLA
3	GeMSS	GeMSS	GeMSS
4	Rainbow	Rainbow	Rainbow
5	CRYSTALS-Dilithium	SPHINCS+	SPHINCS+

Table 27: The top five most energy efficient submissions for functions pertaining to **Digital Signatures**. Results are from **Optimized C Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3.

Analysis of Digital Signatures

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	Picnic	Picnic	Picnic
2	CRYSTALS-Dilithium	CRYSTALS-Dilithium	qTESLA
3	qTESLA	qTESLA	SPHINCS+
4	MQDSS	MQDSS	Luov
5	SPHINCS+	SPHINCS+	Falcon
Rank	**Signing**		
1	Rainbow	CRYSTALS-Dilithium	Falcon
2	qTESLA	qTESLA	qTESLA
3	Falcon	Rainbow	Rainbow
4	CRYSTALS-Dilithium	Luov	Luov
5	Luov	GeMSS	Picnic
Rank	**Verification**		
1	qTESLA	qTESLA	Falcon
2	Falcon	CRYSTALS-Dilithium	qTESLA
3	GeMSS	GeMSS	GeMSS
4	Rainbow	Rainbow	Rainbow
5	CRYSTALS-Dilithium	SPHINCS+	SPHINCS+

Table 27: The top five most energy efficient submissions for functions pertaining to **Digital Signatures**. Results are from **Optimized C Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3.

Lattice-based

Multivariate-based

Other

Analysis of Digital Signatures

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	Picnic (1)	Picnic (1)	Picnic (1)
2	CRYSTALS-Dilithium (2)	CRYSTALS-Dilithium (2)	SPHINCS+ (3)
3	MQDSS (4)	MQDSS (4)	qTESLA (2)
4	qTESLA (3)	qTESLA (3)	Luov (4)
5	Luov (6)	SPHINCS+ (5)	Rainbow (6)
Rank	**Signing**		
1	Rainbow (1)	qTESLA (2)	Rainbow (3)
2	CRYSTALS-Dilithium (4)	CRYSTALS-Dilithium (1)	qTESLA (2)
3	qTESLA (2)	Rainbow (4)	Luov (4)
4	Luov (6)	Luov (4)	GeMSS (6)
5	MQDSS (9)	MQDSS (8)	Picnic (5)
Rank	**Verification**		
1	Rainbow (4)	Rainbow (4)	Rainbow (4)
2	qTESLA (1)	CRYSTALS-Dilithium (2)	qTESLA (2)
3	CRYSTALS-Dilithium (5)	qTESLA (1)	Luov (6)
4	GeMSS (3)	GeMSS (3)	GeMSS (3)
5	Luov (7)	Luov (6)	SPHINCS+ (5)

Table 28: The top five most energy efficient submissions for functions pertaining to **Digital Signatures**. Results are from **Assembly Optimized Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3. Brackets indicate rank in portable C implementation.

Analysis of Digital Signatures

	Level 1	Level 3	Level 5
Rank	**Keypair Generation**		
1	Picnic (1)	Picnic (1)	Picnic (1)
2	CRYSTALS-Dilithium (2)	CRYSTALS-Dilithium (2)	SPHINCS+ (3)
3	MQDSS (4)	MQDSS (4)	qTESLA (2)
4	qTESLA (3)	qTESLA (3)	Luov (4)
5	Luov (6)	SPHINCS+ (5)	Rainbow (6)
Rank	**Signing**		
1	Rainbow (1)	qTESLA (2)	Rainbow (3)
2	CRYSTALS-Dilithium (4)	CRYSTALS-Dilithium (1)	qTESLA (2)
3	qTESLA (2)	Rainbow (4)	Luov (4)
4	Luov (6)	Luov (4)	GeMSS (6)
5	MQDSS (9)	MQDSS (8)	Picnic (5)
Rank	**Verification**		
1	Rainbow (4)	Rainbow (4)	Rainbow (4)
2	qTESLA (1)	CRYSTALS-Dilithium (2)	qTESLA (2)
3	CRYSTALS-Dilithium (5)	qTESLA (1)	Luov (6)
4	GeMSS (3)	GeMSS (3)	GeMSS (3)
5	Luov (7)	Luov (6)	SPHINCS+ (5)

Table 28: The top five most energy efficient submissions for functions pertaining to **Digital Signatures**. Results are from **Assembly Optimized Implementations.** Schemes targeting Level 2 and 4 are included in Level 1 and 3. Brackets indicate rank in portable C implementation.

Lattice-based

Multivariate-based

Other

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Summary and Future Work

- In this work, we measured the energy of the PQC Round 2 candidates, including the required Optimized C Implementation as well as Assembly Optimized Implementations

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Summary and Future Work

- In this work, we measured the energy of the PQC Round 2 candidates, including the required Optimized C Implementation as well as Assembly Optimized Implementations
- Results were categorized by cryptographic function and proposed security level
- Candidates were ranked based on their energy consumption to demonstrate which schemes are most energy efficient

Summary and Future Work

- We do not provide a total energy consumption metric for Digital Signatures due to the nature of their use

- Optimization efforts will shift based on the application for which the digital signature scheme is deployed

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Summary and Future Work

- We do not provide a total energy consumption metric for Digital Signatures due to the nature of their use
- Optimization efforts will shift based on the application for which the digital signature scheme is deployed
- Efficient signing is generally preferred in settings where resource-constrained devices must have a means to transmit authentic data measurements to a base station
- Applications like public-key certification where a single message is signed once and verified by the masses ideally have an efficient verification procedure

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Summary and Future Work

- We do not provide a total energy consumption metric for Digital Signatures due to the nature of their use
- Optimization efforts will shift based on the application for which the digital signature scheme is deployed
- Efficient signing is generally preferred in settings where resource-constrained devices must have a means to transmit authentic data measurements to a base station
- Applications like public-key certification where a single message is signed once and verified by the masses ideally have an efficient verification procedure
- Total energy for KEMs reported for a single key generation, encapsulation and decapsulation, including both ephemeral and general use cases

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Summary and Future Work

- In future extensions of this work, we plan on performing the Optimized C Implementation profiles on the same platform as was used in the Assembly Optimized Implementations

- We hope to use our findings in the future to pinpoint which subroutines of the candidate submissions expend the most energy to provide direction for further optimizations

- Our ranking only provides one metric of evaluation; a wholistic approach should be used when determining which algorithm best suites one's application

Full technical report can be found at
http://cacr.uwaterloo.ca/techreports/2019/cacr2019-03.pdf

Acknowledgements

This research was supported in part through a grant provided by the Natural Sciences and Engineering Research Council of Canada. The authors would also like to thank Tanushree Banerjee for her guidance and support in the preliminary stages of this project.

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