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Standard Lattice-Based Key Encapsulation on Embedded Devices

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Outline

- Motivation
- ~~Post-quantum cryptography and LWE~~
- Introduction to Frodo
- Microcontroller design
- Hardware design
- Results and performance analysis

Motivation

- NIST have started a post-quantum standardisation “competition”.
- The call suggests future rounds will likely involve:
  - Evaluations on constrained devices, such as smart cards,
  - as well as comparisons of the schemes in hardware.
- Why focus on lattice-based / Frodo?
  - Extremely versatile and theoretically sound.
  - Probably the most secure lattice candidate.
  - Less implementations than ideal lattice schemes; has larger keys and no NTT.
  - Frodo is ideal for long-term security and constrained (hardware) platforms.

Frodo: Take off the ring!

The design philosophy of FrodoKEM [ABD^{+}] combines:

- Conservative yet practical post-quantum constructions.
- Security derived from cautious parameterizations of the well-studied learning with errors problem.
- Thus, close connections to conjectured-hard problems on generic, “algebraically unstructured” lattices.
- Parameter selection is far less constrained than vs ideal lattice schemes.

Frodo: Why should we take off the ring?

These qualities are appealing for practitioners;

- Many IoT use cases require long-term, efficient cryptography.
- Post-quantum cryptography is becoming essential.
- Microcontrollers and FPGAs will play a role in future technologies.
- Suitable for use cases such as satellite communications and V2X.

Frodo: key encapsulation from standard lattices

Algorithm 1 The FrodoKEM encapsulation (shortened)

procedure ENCAPS($pk =$ seed$_{\mathbf{A}}||\mathbf{b}$)
  Choose a uniformly random key $\mu \leftarrow U(\{0,1\}^{\mathsf{len}_\mu})$
  Generate pseudo-random values seed$_{\mathbf{E}}||\mathbf{k}||\mathbf{d} \leftarrow G(pk||\mu)$
  Sample error matrix $\mathbf{S}', \mathbf{E}' \leftarrow$ Frodo.SampleMatrix(seed$_{\mathbf{E}}, \bar{m}, n, T_\chi, \cdot$)
  Generate the matrix $\mathbf{A} \in \mathbb{Z}_q^{n \times n}$ via $\mathbf{A} \leftarrow$ Frodo.Gen(seed$_{\mathbf{A}}$)
  Compute $\mathbf{C}_1 \leftarrow \mathbf{S}'\mathbf{A} + \mathbf{E}'$
  Sample error matrix $\mathbf{E}'' \leftarrow$ Frodo.SampleMatrix(seed$_{\mathbf{E}}, \bar{m}, \bar{n}, T_\chi, \cdot$)
  Compute $\mathbf{C}_2 \leftarrow \mathbf{S}'\mathbf{B} + \mathbf{E}'' +$ Frodo.Encode(μ)
  Compute $\mathbf{ss} \leftarrow F(\mathbf{c}_1||\mathbf{c}_2||\mathbf{k}||\mathbf{d})$
  return ciphertext $\mathbf{c}_1||\mathbf{c}_2||\mathbf{d}$ and shared secret $\mathbf{ss}$
end procedure

Frodo: key encapsulation from standard lattices

FrodoKEM is comprised of a number of key modules:

- Matrix-matrix multiplication, up to sizes 976.
- Uniform and “Gaussian” error generation.
- Random oracles via cSHAKE for CCA security.

A massive design challenge was to balance **memory utilisation**, whilst not deteriorating the **performance** too much to not overexert the limited computing capabilities of the embedded devices.

FrodoKEM on constrained devices

FrodoKEM has a number of design options we cover:

- Both sets of parameters;
  - FrodoKEM-640 aims to match AES-128 security.
  - FrodoKEM-976 aims to match AES-192 security.
- PRNG from AES and cSHAKE modules.
- We focus on FrodoKEM, rather than the previous key exchange scheme FrodoCCS [**?**].

FrodoKEM on ARM

Contribution overview:

- Optimized memory allocation that makes the implementation small enough to fit on embedded microcontrollers.
- An assembly multiplication routine that speeds up our implementation, realizing a performance that fits the requirements of common use-cases.
- Utilises constant runtime to protect against simple side-channel analysis.
- FrodoKEM-640 has a total execution time of 836 ms.

FrodoKEM on ARM

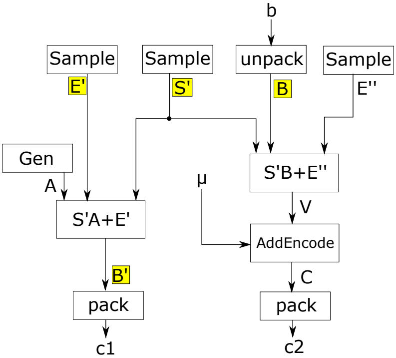


Figure: Flowchart of the encapsulation.

- We analysed the memory occupancy during each operation.
- Reusing already allocated memory wherever possible to
- Minimizing the memory usage for all designs.

Results and Comparisons

- Clear difference between AES and cSHAKE implementations.
- Outperforms other Frodo design, but much slower than Kyber / NewHope.

Table: Cycle counts for our full microcontroller implementations (at 168 MHz).

Implementation	Platform	Security Level	Cycle counts
FrodoKEM-640-AES	Cortex-M4	128 bits	140,398,055
FrodoKEM-976-AES	Cortex-M4	192 bits	315,600,317
FrodoKEM-640-cSHAKE	Cortex-M4	128 bits	310,131,435
FrodoKEM-976-cSHAKE	Cortex-M4	192 bits	695,001,098
FrodoKEM-640-cSHAKE [pqm]	Cortex-M4	128 bits	318,037,129
KyberNIST-768 [pqm]	Cortex-M4	192 bits	4,224,704
NewHopeUSENIX-1024 [AJS16]	Cortex-M4	255 bits	2,561,438
ECDH scalar multiplication [DHH+15]	Cortex-M0	pre-quantum	3,589,850

Results and Comparisons

- Despite being slower, cSHAKE requires less memory than AES.
- Our memory optimisations save between 30-40% compared to PQM4.
- Versus the referenced designs we also save 66% in peak stack usage.

Table: Stack usage in bytes for our microcontroller implementations.

	FrodoKEM-AES		FrodoKEM-cSHAKE		FrodoKEM-cSHAKE [pqm]	
Operation	$n = 640$	$n = 976$	$n = 640$	$n = 976$	$n = 640$	% Savings
Keypair	23,396	35,484	22,376	33,800	36,536	39%
Encaps	41,292	63,484	37,792	57,968	58,328	35%
Decaps	51,684	63,628	48,184	58,112	68,680	30%

FrodoKEM on FPGA

Contribution overview:

- Proposes a generic LWE multiplication core which computes vector-matrix multiplication and error addition.
- Generates future random values in parallel, minimising delays between vector-matrix multiplications.
- Hybrid pre-calculated / on-the-fly memory management is used, which continuously updates previous values.
- Ensures constant runtime by parallelising other modules with multiplication.
- FrodoKEM-640 has a total execution time of 60 ms.

FrodoKEM on FPGA

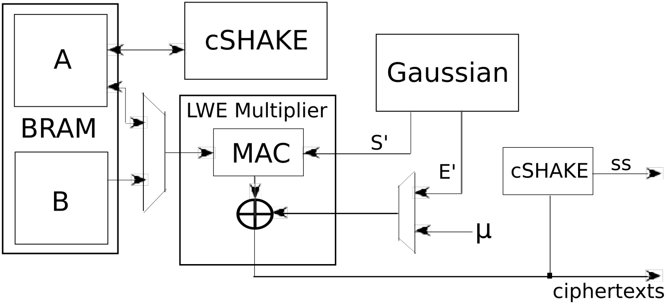


Figure: An overview of our FPGA design of FrodoKEM Encapsulation.

Results and Comparisons

- Competes with NewHope area consumption, but much slower performance.
- Huge savings in BRAM compared to LWE Encryption [HMO+16].

Table: FPGA consumption and performance of our proposed designs, benchmarked on Artix-7.

Cryptographic Operation	LUT/FF	Slice	DSP	BRAM	MHz	Ops/sec
FrodoKEM-640 Keypair	6621/3511	1845	1	6	167	51
FrodoKEM-640 Encaps	6745/3528	1855	1	11	167	51
FrodoKEM-640 Decaps	7220/3549	1992	1	16	162	49
FrodoKEM-976 Keypair	7155/3528	1981	1	8	167	22
FrodoKEM-976 Encaps	7209/3537	1985	1	16	167	22
FrodoKEM-976 Decaps	7773/3559	2158	1	24	162	21
cSHAKE*	2744/1685	766	0	0	172	1.2m
Error+AES Sampler*	1901/1140	756	0	0	184	184m
NewHopeUSENIX Server [OG17]	5142/4452	1708	2	4	125	731
NewHopeUSENIX Client [OG17]	4498/4635	1483	2	4	117	653
LWE Encryption [HMO+16]	6078/4676	1811	1	73	125	1272

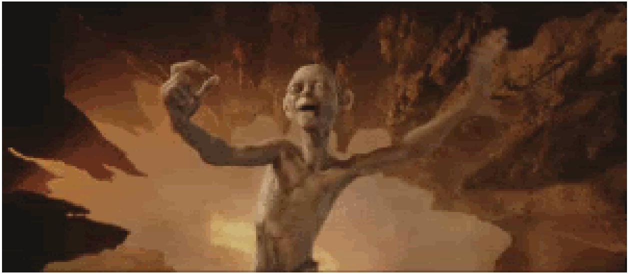
Conclusions

- We show that hardware significantly minimises the performance distance between standard and ideal lattice-based KEM, able to utilise less than 2000 slices and remain practical.
- Memory optimisations for microcontrollers show 66% savings vs reference design and 40% vs optimised PQM4 design.

Conclusions

- Our results show the efficiency of FrodoKEM and help to assess the practical performance of a possible future post-quantum standard.

Although rings are still good to use, unless you're Gollum...



Thank you for listening. Any questions?

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