From Theory to Practice

Integrating Post-Quantum Solutions in Real-World Systems

ECW 2024

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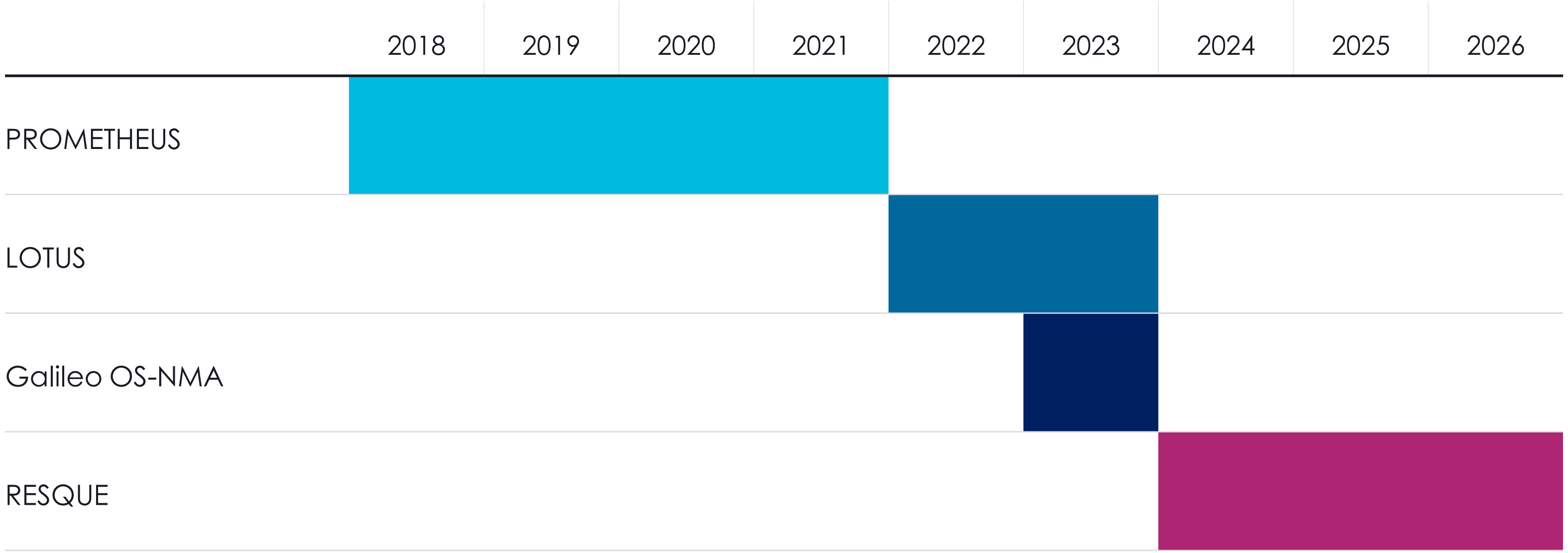
Introduction



Part I: Applications

Post-quantum Anonymous Credentials
Hybrid Authenticated Key Exchange
Post-quantum mechanisms in Galileo OS-NMA

Part II: Implementations

Crypto-agility in crypto software libraries
Side-channels attacks and their countermeasures
Hybrid hardware-software architectures

APPLICATIONS OF POST-QUANTUM CRYPTOGRAPHY

Post-quantum Anonymous Credentials

Hybrid Authenticated Key Exchange

Post-quantum mechanisms in Galileo OS-NMA

PROMETHEUS
PRivacy preserving pOst-quantuM systEms from advanced crypTograpHic mEchanisms Using latticeS

PROMETHEUS – H2020 EU project 2018-2023

- EU collaborative project on **post-quantum protection of personal data** :
  - 8 academic / 4 industrial partners,
  - France/Germany/United Kingdom/Spain/Netherlands/Israel

- Scope : protect **children privacy** when browsing a **video streaming service.**

- Goal : to allow a user to **gain access to age-appropriate video** without having to **disclose personal information** to the service.

> Our solution QPACE – Quantum Proof Anonymous Credential Engine

Preserving privacy with post-quantum anonymous credentials

The **user** aims to prove legitimate access to a **service** that enforces a **verification** (identity, age, etc.) while preserving its **privacy**.

Step 1 : the user requests a **credential** that will be delivered by a trusted third party.
Step 2 : credentials are used by the QPACE to generate **ephemeral tokens** which will be verified by a service.

Lattice-Based Group signature **[dPLS18]**
RSIS/RLWE/NTRU assumptions → quantum resistant

NIZK Proof system **[ALS20]**

RSIS = (Ring)-Short Integer Solution
RLWE = (Ring)-Learning With Errors
NTRU-based cryptosystem

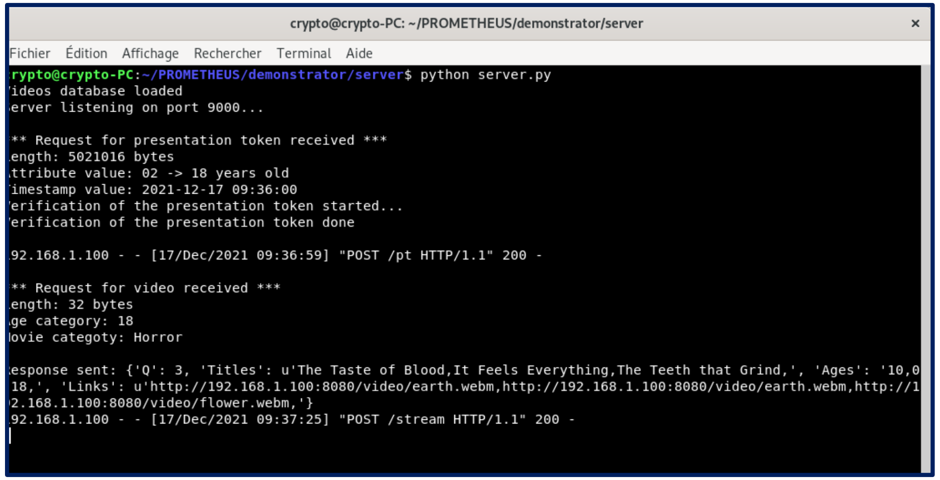
[dPLS18] Rafaël del Pino, Vadim Lyubashevsky and Gregor Seiler. Lattice-Based Groupe Signatures and Zero-Knowledge Proofs of Automorphism Stability. CCS 2018.

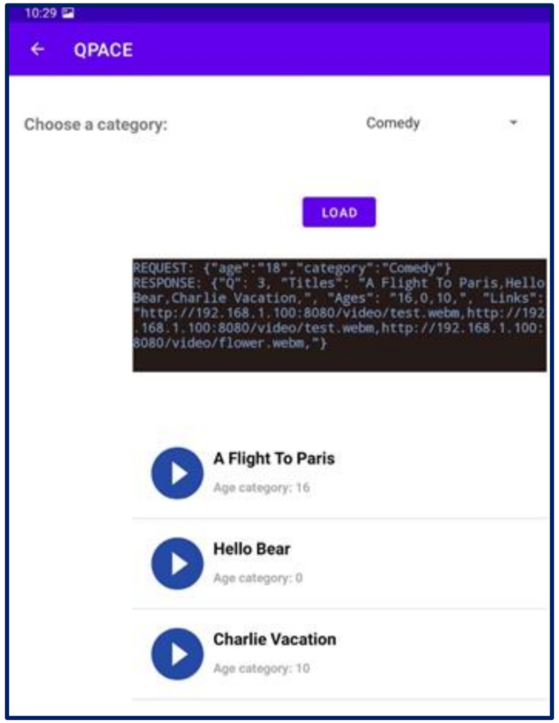
[ALS20] Thomas Attema, Vadim Lyubashevsky and Gregor Seiler. Practical Product Proofs for Lattice Commitments. CRYPTO 2020.

Performances of our QPACE demonstrator

Transmission + data parsing
~ few seconds

Average: ~ 5 seconds
Worst-case ~10 seconds





Presentation Token (average size 5 MB)	CPU cycles (min / average / max)	Seconds (min / average / max)
Generation	1 / **5** / 20	0.5 / **2** / 6
Verification	5.4 / **5.43** / 5.5	0.169 / **0.17** / 0.174
Total	6.4 / **10.43** / 25.5	0.679 / **2.17** / 6.174

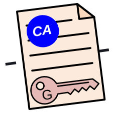
Room for improvements
- ✓ faster proof system
- ✓ better data parsing
- ✓ only a demonstrator

RESQUE – BPI France 2023-2026

HSM

- **Infrastructures protection**
- *Performances ++*
- *Protection against Side Channel Attacks*

certificates provider



VPN gateway / encryptor

- **Protection of communications**
- *Post-quantum evolution of IPsec IKEv2 standard*
- *Integration of an hybrid AKE*

Thales MISTRAL + Hybrid AKE solution

Thales DIS dedicated co-processor (HSM Luna) for HW accelerations

Algorithms :
- Dilithium (**ML-DSA**)
- Kyber (**ML-KEM**)

ML = Module-Lattice-Based

Ipsec tunnel

VPN client

- **Remote workers protection**

Efficient **hybrid solution** toward a safe, progressive post-quantum cryptography to **protect companies, administration and remote workers.**

Hybrid Authenticated Key Exchange in RESQUE

Aim : Adapt the IPsec DR specification of IKEv2 to add Hybrid Key Exchange and Hybrid Authentication

ANSSI views on PQC transition [1] :

Hybrid Key Exchange: ETSI's [2] hybridation modes for Key Encapsulation Mechanisms are recommended

Hybrid Authentication:

- Hybridation is made by combining classical and PQ signatures
- No choice of hybrid certificates : « designs and security proofs of such hybrid certificate protocols are still currently moving »

[1] ANSSI views on the Post-Quantum Cryptography transition (2023 follow up) (December 21, 2023)

[2] ETSI. Quantum-safe hybrid key exchanges

Hybrid AKE in RESQUE – our solutions

Hybrid Key Exchange: one solution

Proposed Standard RFC 9370 proposes a solution to add multiple key exchanges on IKEv2

→ We **adapted it** by replacing hybridation modes by ETSI's ones.

Hybrid authentication: three solutions

At the protocol level, by using **experimental RFC 4379** to allows multiple authentication exchanges

At primitive level, by using **hybridized certificates**:

- One adopted by the **LAMPS working group**, not yet formalized as an RFC (draft-ietf-lamps-pq-composite-sigs-02)
- One based on the **multiple-algorithm certificate** defined in "X.509 : Information technology - Open Systems Interconnection - The Directory: Public-key and attribute certificate frameworks"

Post-quantum mechanisms in Galileo OS-NMA (2023)

> Context:

- Project **E-GIANTS** : **E**uropean **G**NSS[1] **I**mproved **A**uthentication **S**olutions
- Requested by the European Commission
- 6 industrial partners

> Our mission: Cryptographic support for the Galileo OS-NMA mechanism

- Review of the current OS-NMA[2] mechanism
- Identification of possible cryptographic improvements for the long term (> 2030)

→ **Consider post-quantum mechanisms**

1. **GNSS**: **G**lobal **N**avigation **S**atellite **S**ystem
2. **OS-NMA**: Galileo **O**pen **S**ervice **N**avigation **M**essage **A**uthentication

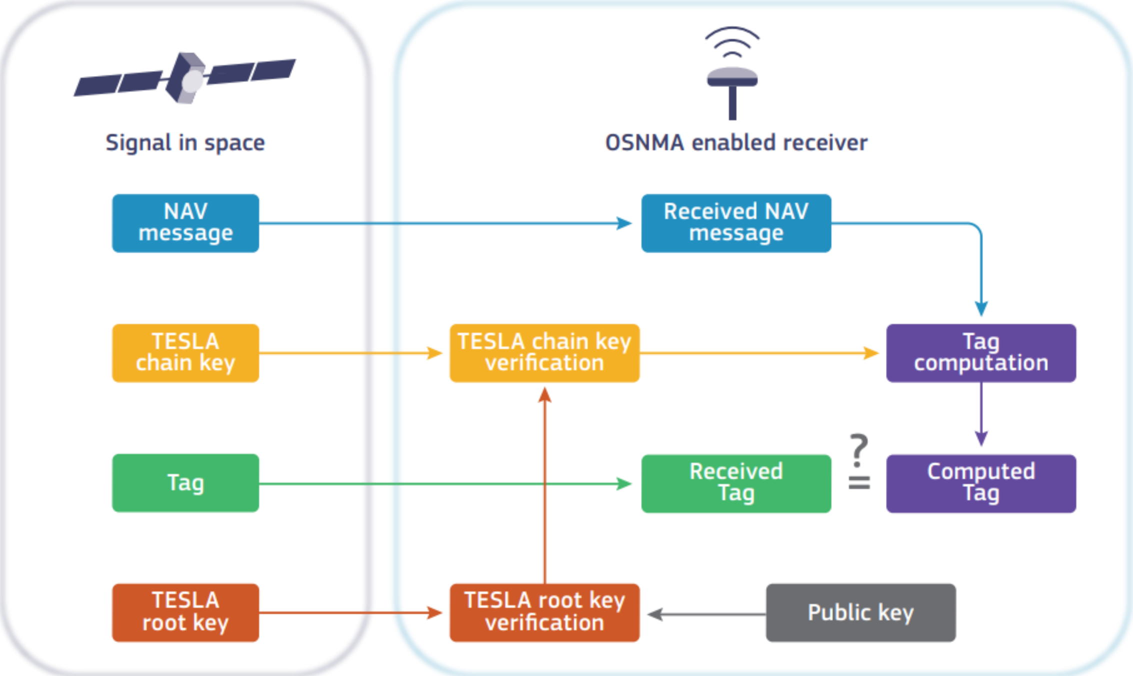
Post-quantum mechanisms in Galileo OS-NMA

> OS-NMA:

- Open, free of charge positioning and timing service
- Authenticates the messages broadcast by the satellites
- Based on **TESLA protocol** [RFC 4082]

TESLA chain derivation
SHA-256
SHA3-256

TESLA root key verification
ECDSA-256
ECDSA-512



Tag computation
HMAC-SHA-256
AES-CMAC

Public key verification
Merkle tree
(SHA256 / SHA3-256)
Or certificates (ECDSA-256)

Source: Galileo High Accuracy Service (HAS) Info Note. © European Union Agency for the Space Programme, 2021

Post-quantum mechanisms in Galileo OS-NMA

> Suggested improvements:

- Symmetric algorithms: increase the parameter size
- Digital signatures: use post-quantum schemes

} According to the recommandations (hybridation, use of standard PQC schemes and parameter sets)

> Principal constraint: The Signal in Space has a very limited bandwidth

- Transmit PQ signatures within the Signal in Space seems impossible

> Possible solutions:

- Increase the Signal In Space bandwidth
- Preload some data and signatures if possible

No specific algorithms selected yet, work still in progress!

Part I: applications – what we learned so far

> Anonymous Credentials

PQ algorithms **not mature yet** → **waiting time** before accessing the service, need to **reduce PT generation time** (improve primitives and performances?)

> Hybrid KEMs and certificates

Lot of (too much?) solutions but:

- not always fully **mature**, need **adaptations**
- not always **compliant** with **official recommendations** (hybrid KEMs ≠ ANSSI recos)

> PQ for space communications

Need to **increase bandwidth** or **pre-load** as much data as possible

Only **preliminary studies**, lack of **mature solutions** for space systems

IMPLEMENTATIONS OF POST-QUANTUM CRYPTOGRAPHY

Crypto-agility in crypto software libraries

Side-channels attacks and their countermeasures

Hybrid hardware-software architectures

What is crypto-agility ?

Generic interface providing services: encryption, signature, hashing, KEM, etc.

✓ Different **algorithms, parameters, modes** and **implementations** → flexible input/output sizes, internal state, etc.

SHA256, SHA512, SHAKE256_384, HMAC-SHA256, etc. → **HASHFunction**

XMSS_2/5/10/14_SHAKE256_256, XMSS_2/16_SHAKE256_512 → **Signature**

Regular implementation, specific instruction set enabled, masked version against SCAs, etc.

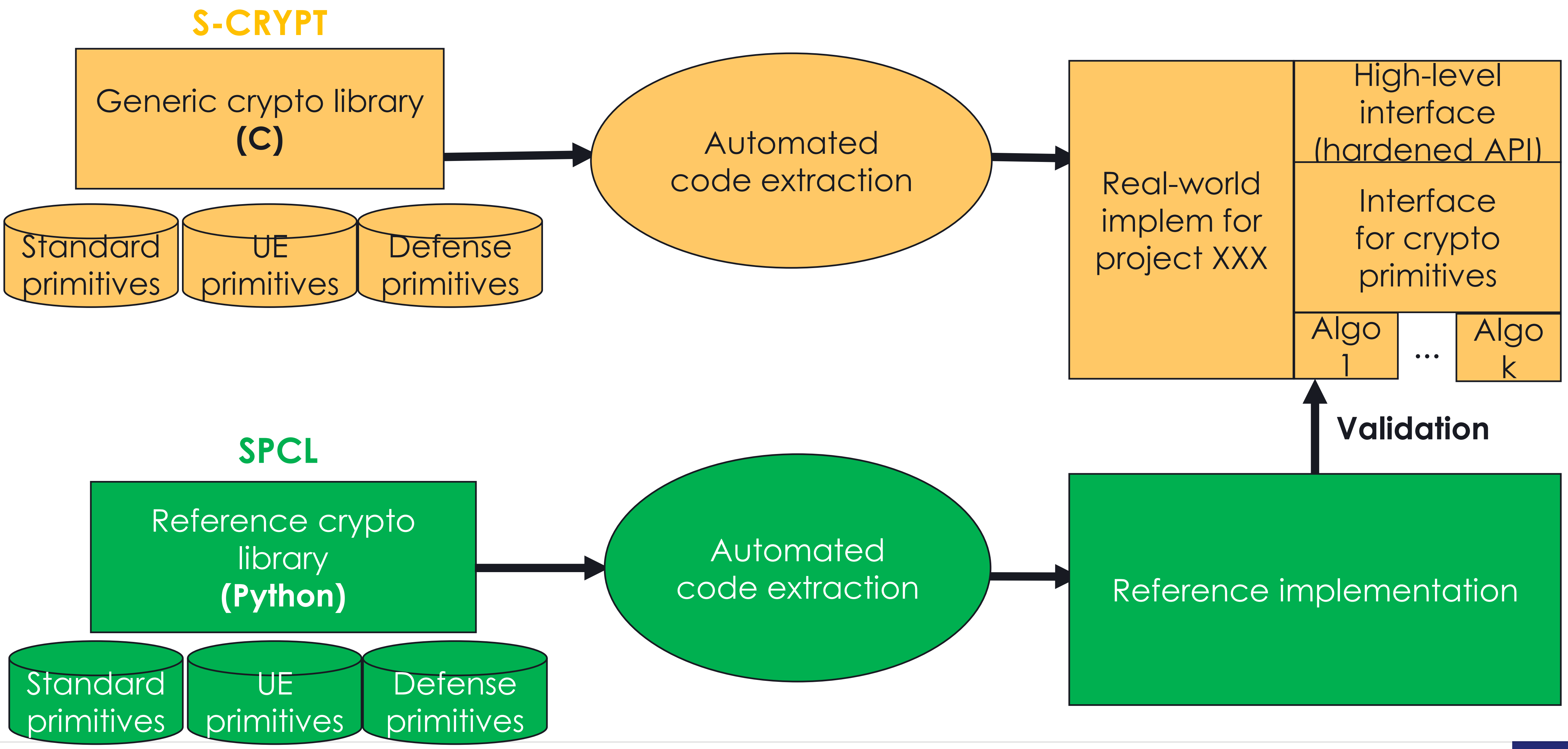
✓ Common **validation** process→ **CAVP** (NIST Cryptographic Algorithm Validation Program) and **tests vectors** specified by standards and norms

Facilitates migration toward post-quantum algorithms, but <u>not limited to PQ</u>

✓ Generic interfaces with **interchangeable components** (algorithms, parameters, etc.)

✓ Crypto is constantly evolving → need **flexibility** to **anticipate** future changes

S-CRYPT (real-world implementation) / SPCL (reference implementation)



Integration of many primitives, included PQ algorithms

> SPCL (Python reference library)

XMSS (RFC 8391), SPHINCS+(SLH-DSA), Dilithium (ML-DSA), Falcon (FN-DSA), FrodoKEM, etc.

> S-CRYPT (C real-world implementation)

✓ XMSS_2/5/10/14_SHAKE256_256, XMSS_2/16_SHAKE256_512

✓ FrodoKEM_640/976/1344_AES/SHAKE

✓ Wrapping of *libecc* (Elliptic Curve primitives) and *liboqs* (many PQ algorithms) for **software risk assessment**

✓ **Hardened interface**: tests for vulnerabilities in memory allocation, incorrect parameters, code coverage, fuzzing, etc.

S-CRYPT: optimisation and hardening

XMSS

- ✓ **parallelisation** in Merkle trees and authentication path construction
- ✓ better **time-memory tradeoffs**
  - **BDS algorithm**, **full tree in memory** during KeyGen to minimize signature time (30min ↘ few min)

Hardened interface

- ✓ tests for vulnerabilities in **memory allocation**
- ✓ incorrect **parameters**
- ✓ **code coverage**, **fuzzing**, etc. → **fuzzing on XMSS_BDS resulted in several bugs identified**

Simple crypto library encompassing only the strict necessity

Hybrid hardware-software architectures for PQ algorithms

> Step 1: software implementation

Which SW implementation?

> Step 2: benchmarking

Execution time, number of operations, most used functions…

> Step 3: identification of bottlenecks

Which **operations** or **subparts** of the algorithm would benefit from HW acceleration?

> Step 4: partial HW implementation VS full HW implementation

Full HW implementation is complex, costly, not flexible (crypto-agility) and not always necessary → best to **accelerate specific operations**

Dedicated HW accelerators for PQ building blocks

PQ algorithm	HW acceleration
BIKE	✓ MUL for large & sparse polynomials over binary rings ✓ Decoder
FrodoKEM	✓ SHAKE (eXpendable Output Function) ✓ Sampling ✓ Matrix multiplication
Dilithium (ML-DSA)	✓ Number Theoretic Transform (NTT) ✓ Fast Fourier Transform (FFT) ✓ Sampling
Kyber (ML-KEM)	SHAKE
Falcon (FN-DSA)	✓ NTT, FFT ✓ Floating point operations ✓ Gaussian sampling
XMSS (RFC 8391)	Full HW implementation

LOTUS : HW acceleration for BIKE and FrodoKEM (2021-2023)

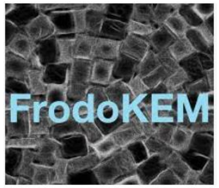
1

Study of 6 KEMs

6 post-quantum KEMs studied
3 Lattice based
CRYSTALS KYBER, FrodoKEM, NTRU
3 Code based
ROLLO-I, BIKE, Classic McEliece
Bibliographical study
Implementation technics
Side-channel attacks
& Counter-measures
Implementation of a reference cryptographic library

2

Selection of 2 KEMs



BIKE

Embedded SW implementation with highest security parameters (level 5)
Side channel analysis and counter-measure implementation
Partial HW acceleration

3

Results

Two attack paths over the most critical operations were partially or totally exploitable

Implemented countermeasures against all these attacks

HW acceleration x20 (level 5)

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Hybrid hardware-software architecture in RESQUE

- ✓ Analysis of Dilithium (ML-DSA) and Kyber (ML-KEM) schemes to determine **which internal building blocks** should be **HW-accelerated by the HSM Luna (Thales DIS)**:

  eXpendable Output Functions **SHAKE**

  Arithmetic over $\mathrm{R}_q = \mathbb{Z}_q[X]/(X^n+1)$ with flexibility over the choice of q

  → necessary for crypto-agility and protection against SCA

- ✓ **State-of-the-art of existing HW implementations** for ML-DSA and ML-KEM

  → necessary to choose the most pertinent implementation and reach the best **flexibility-efficiency-resources tradeoff**

  crypto-agility | latency and bandwith | surface

Side-channels attacks and countermeasures in RESQUE (2023-2026)

The work so far

- ✓ State-of-the-art of **side-channel attacks** against **Dilithium (ML-DSA)** and **Kyber (ML-KEM).**
- ✓ State-of-the-art of applicable **countermeasures**.
- ✓ Several **Working Groups** aiming at **solving open problems** such as

    How to mask critical variables and challenging operations?

    How to improve existing attacks and countermeasures?

    How to reduce the performance gap between non-protected implementations and protected ones (new gadgets, etc.)?

Part II: implementations – what we learned so far

> Hybridation

- Many possibilities but nothing fully **mature or compliant** with recommandations
- Lack of **standards and documentation** (ex. hybrid certificates)

> Advanced primitives

- Anonymous Credentials, Attribute-Based Encryption, etc. also **lack maturity**
- Need more investigation and **better performances**

> Secure, flexible and optimized implementations

- Every algorithm relies on specific mechanisms → **unique challenges and solutions**
- Crypto-agility requires more work but provides **flexibility to anticipate the future**

Contact

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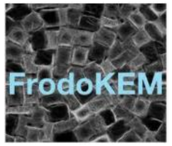
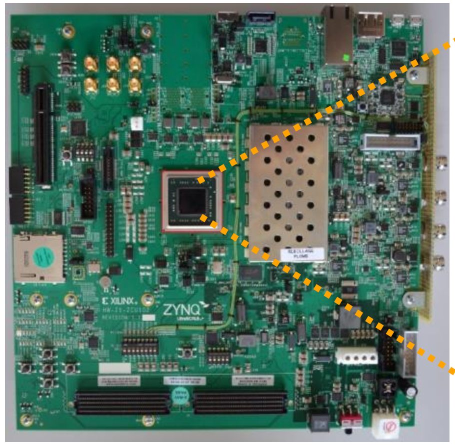
Annex: LOTUS hardware platform

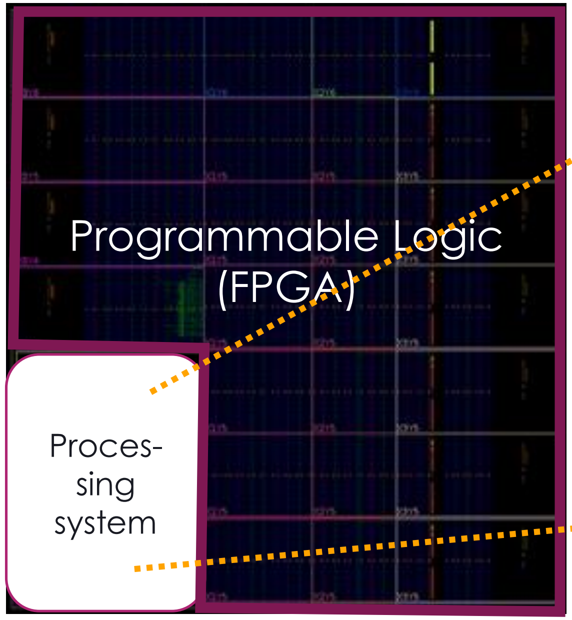
Embedded Software



BIKE



Xilinx Ultrascale+ ZCU102 board



Xilinx ZYNQ Ultrascale+ MPSOC FPGA component