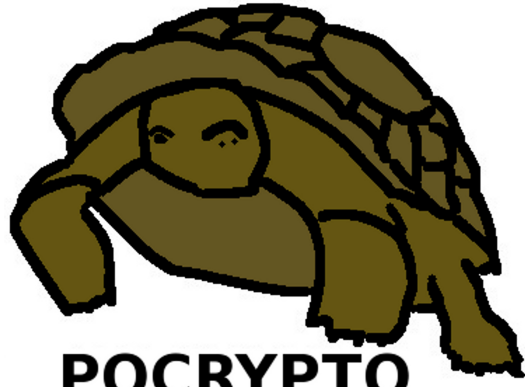
# Results of PQCRYPTO (ICT-645622) Post-quantum cryptography for long-term security

Tanja Lange




19 September 2018

FutureTPM Workshop

# Post-Quantum Cryptography for Long-term Security

- Project funded by EU in Horizon 2020.
- Starting date 1 March 2015, project duration 3 years.
- 11 partners from academia and industry, TU/e is coordinator












# Work packages

Technical work packages

- WP1: Post-quantum cryptography for small devices
  Leader: Tim Güneysu, co-leader: Peter Schwabe
- WP2: Post-quantum cryptography for the Internet
  Leader: Daniel J. Bernstein, co-leader: Wouter Castryck
- WP3: Post-quantum cryptography for the cloud
  Leader: Nicolas Sendrier, co-leader: Christian Rechberger

Non-technical work packages

- WP4: Management and dissemination
  Leader: Tanja Lange
- WP5: Standardization
  Leader: Walter Fumy and Frank Morgner

# General PQCRYPTO achievements

- Lots of papers: more than 130 publications, including one Nature paper.
- Widely used "Initial Recommendations" document giving PQCRYPTO recommendations of conservative systems.
- Many presentations (slides are online, some talks have videos).
  - 9 presentations of PQCRYPTO.
  - 32 general presentations of post-quantum cryptography.
  - 31 presentations at (summer) schools.
  - 77 focused presentations of scientific results.
- 17 deliverables from the scientific WPs.
- 22 fully worked-out submissions to NIST.
- Event highlights:
  - PQCRYPTO summer school (126 students);
  - PQCrypto conference 220 participants.
- Active twitter feed `https://twitter.com/pqc_eu`.

# Initial recommendations

- **Symmetric encryption** Thoroughly analyzed, 256-bit keys:
  - AES-256
  - Salsa20 with a 256-bit key

  Evaluating: Serpent-256, ...
- **Symmetric authentication** Information-theoretic MACs:
  - GCM using a 96-bit nonce and a 128-bit authenticator
  - Poly1305
- **Public-key encryption** McEliece with binary Goppa codes:
  - length $n = 6960$, dimension $k = 5413$, $t = 119$ errors

  Evaluating: QC-MDPC, Stehlé-Steinfeld NTRU, ...
- **Public-key signatures** Hash-based (minimal assumptions):
  - XMSS with any of the parameters specified in CFRG draft
  - SPHINCS-256

  Evaluating: HFEv-, ...

# WP1: Post-quantum cryptography for small devices

- Find post-quantum secure cryptosystems suitable for small devices in power and memory requirements (e.g. smart cards with 8-bit or 16-bit or 32-bit architectures, with different amounts of RAM, with or without coprocessors).
- Develop efficient implementations of these systems.
- Investigate and improve their security against implementation attacks.
- Deliverables include reference implementations and optimized implementations for software for platforms ranging from small 8-bit microcontrollers to more powerful 32-bit ARM processors.
- Deliverables also include FPGA and ASIC designs and physical security analysis.

# Primary Target Platforms

## Software

- ARM Cortex M4
  - 32-bit microcontroller
  - up to 168 MHz
  - up to 1 MB Flash, 192 KB RAM
  - Cheap development boards ($\approx$ 12 Euros) and open toolchain

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## Hardware

- Xilinx Spartan-6 FPGA
  - 45nm process technology
  - *"lowest total cost for high-volume applications"*

# Integration: pqm4

- Library and testing/benchmarking framework
- Easy to add schemes using NIST API
- Optimized SHA3 shared across primitives
- Focus on PQCRYPTO submissions to NIST, medium security

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- Focus on PQCRYPTO submissions to NIST, medium security
- Run functional tests of all primitives and implementations:

```
python3 test.py
```

- Generate testvectors, compare for consistency (also with host):

```
python3 testvectors.py
```

- Run speed and stack benchmarks:

```
python3 benchmarks.py
```

- Easy to evaluate only subset of schemes, e.g.:

```
python3 test.py newhope1024cca sphincs-shake256-128s
```

# pqm4 results KEM/PKE

| | |
|---|---|
| BIG QUAKE | ? |
| BIKE | ? |
| Classic McEliece | ✗ |
| CRYSTALS-Kyber | ✓ |
| DAGS | ? |
| FrodoKEM | ✓ |
| KINDI | ✓ |
| NewHope | ✓ |
| NTRU-HRSS-KEM | ✓ |
| NTRU Prime | ✓ |
| Post-quantum RSA-Encryption | ✗ |
| Ramstake | ✗(?) |
| SABER | ✓ |
| (SIKE) | ✓ |

# pqm4 results signatures

| | |
|---|---|
| CRYSTALS-Dilithium | ✓ |
| GUI | ✗ |
| LUOV | ? |
| MQDSS | ✗(?) |
| Picnic | ✗ |
| Post-quantum RSA-Signature | ✗ |
| qTESLA | almost certainly yes |
| Rainbow | ? (probably no) |
| SPHINCS+ | ✓ |

# WP2: Post-quantum cryptography for the Internet

- Find post-quantum secure cryptosystems suitable for busy Internet servers handling many clients simultaneously.
- Develop secure and efficient implementations.
- Integrate these systems into Internet protocols.
- Deliverables include software library for all common Internet platforms, including large server CPUs, smaller desktop and laptop CPUs, netbook CPUs (Atom, Bobcat, etc.), and smartphone CPUs (ARM).
- Aim is to get high-security post-quantum crypto ready for the Internet.

# WP2 software library: `libpqcrypto`

14 March 2018: Publicly released https://libpqcrypto.org.

77 cryptographic systems from 19 of the 22 PQCRYPTO submissions:

- BIG QUAKE
- Classic McEliece
- CRYSTALS-DILITHIUM
- CRYSTALS-KYBER
- DAGS
- FrodoKEM
- Gui
- KINDI
- LUOV
- MQDSS
- NewHope
- NTRU-HRSS-KEM
- NTRU Prime
- Picnic
- qTESLA
- Rainbow
- Ramstake
- SABER
- SPHINCS+

# 50 signature systems

CRYSTALS-DILITHIUM: `crypto_sign_dilithium{2,3,4}`

Gui: `crypto_sign_gui{184,312,448}`

LUOV:
`crypto_sign_luov{863256,890351,8117404,4849242,6468330,8086399}`

MQDSS: `crypto_sign_mqdss{48,64}`

Picnic: `crypto_sign_picnicl{1,3,5}{fs,ur}`

qTESLA: `crypto_sign_qtesla{128,192,256}`

Rainbow: `crypto_sign_rainbow{1a,1b,1c,3b,3c,4a,5c,6a,6b}`

SPHINCS+:
`crypto_sign_sphincs{f,s}{128,192,256}{haraka,sha256,shake256}`

# 27 encryption systems

BIG QUAKE: `crypto_kem_bigquake{1,3,5}`

Classic McEliece: `crypto_kem_mceliece{6960119,8192128}`

CRYSTALS-KYBER: `crypto_kem_kyber{512,768,1024}`

DAGS: `crypto_kem_dags{3,5}`

FrodoKEM: `crypto_kem_frodokem{640,976}`

KINDI: `crypto_kem_kindi{256342,256522,512222,512241,512321}`

NewHope: `crypto_kem_newhope{512,1024}cca`

NTRU-HRSS-KEM: `crypto_kem_ntruhrss701`

NTRU Prime: `crypto_kem_{ntrulpr,sntrup}4591761`

Ramstake: `crypto_kem_ramstakers{216091,756839}`

SABER: `crypto_kem_{lightsaber,saber,firesaber}`

# NIST submissions vs. `libpqcrypto`

Each NIST submission includes software:

- a reference C implementation;
- often additional implementations providing better performance.

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- command-line signature/verification/encryption/decryption tools;

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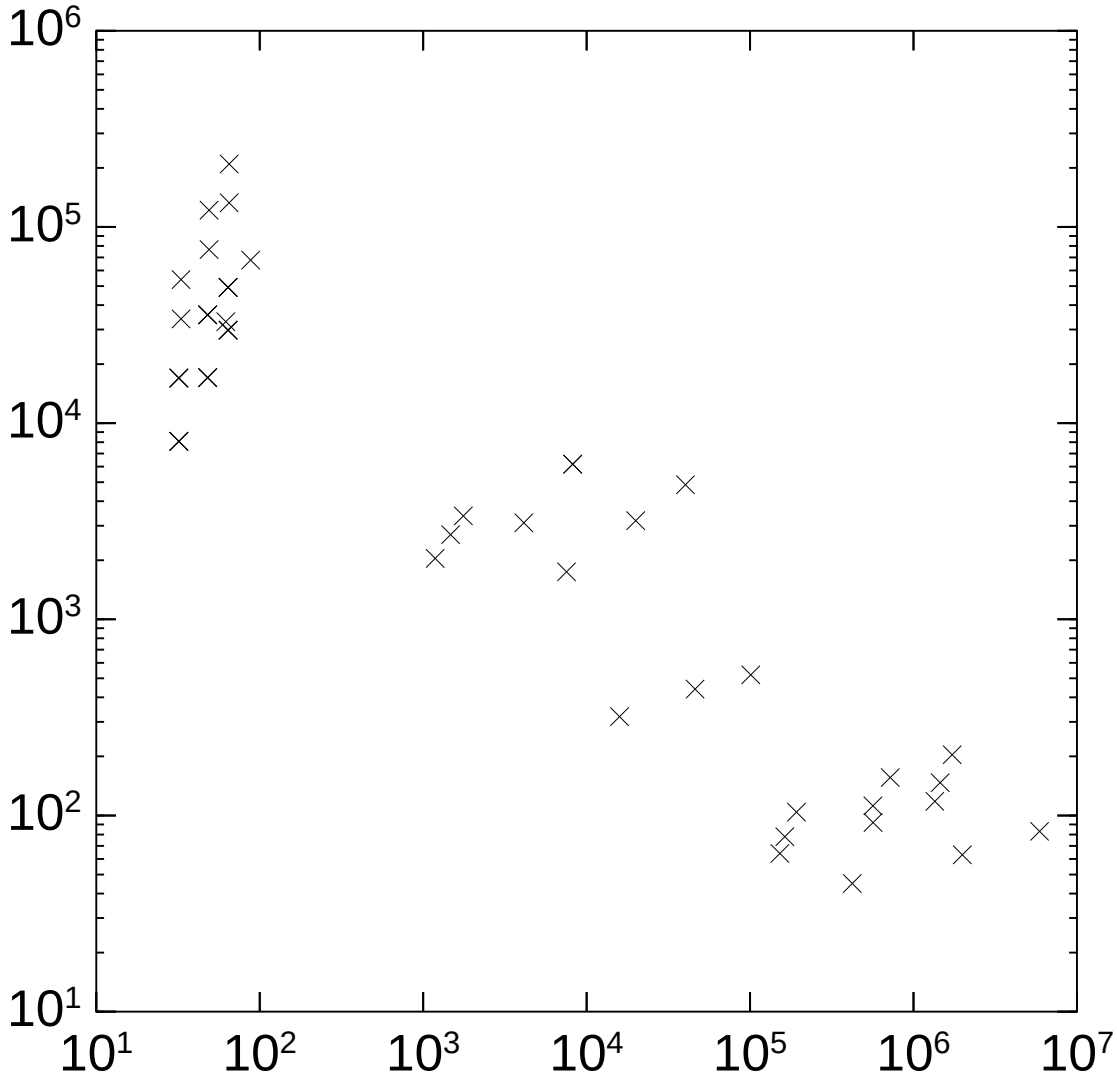
- a unified Python interface;
- command-line signature/verification/encryption/decryption tools;
- command-line benchmarking tools.

# Signature size (vertical) vs. public-key size (horizontal)



# WP3: Post-quantum cryptography for the cloud

- Provide 50 years of protection for files that users store in the cloud, even if the cloud service providers are not trustworthy.
- Allow sharing and editing of cloud data under user-specified security policies.
- Support advanced cloud applications such as privacy-preserving keyword search.
- Work includes public-key and symmetric-key cryptography.
- Prioritize high security and speed over key size.

# WP3 – Post-quantum cryptography for the cloud

- Encrypt at home
  - Main target: authenticated encryption.
  - Quantum cryptanalysis of symmetric schemes.
  - Grover/quantum random walk gives subtle advantages in linear and differential cryptanalysis.
  - Some modes of operation for authenticated encryption can get broken in some quantum models.
- Share files
  - Main targets: digital signature, public-key encryption.
  - Quantum cryptanalysis of public-key schemes.
  - Provide foundations and support for the design of post-quantum cryptosystems.
- Advanced applications
  - Keywords: searchable encryption, multi-party computation, fully homomorphic encryption.
  - Related topics: secret sharing, oblivious transfer, private information retrieval, locally decodable codes.

# WP5: Standardization

Objectives:

> *Make the project visible [. . . ] by providing dissemination material by which the project's results will be submitted for consideration by international standardization bodies (SDOs) such as ISO, ETSI or IEEE.*
> *Organize the project's standardization activities which are relevant both for communicating the project's outcomes and getting valuable feedback from standardization expert groups.*

# Major Players for Standardization of Cryptography

- **ISO/IEC JTC 1/SC 27**: Information technology – Security techniques
  Standardization of generic IT security services and techniques
- **ISO/TC 68 SC 2**: Financial Services, security
- **NIST**: National Institute of Standards and Technology
  Issues standards and guidelines as Federal Information Processing Standards (FIPS) for use by the US government
- **IETF and IRTF Crypto Forum Research Group (CFRG)**:
  Issues RFC's for cryptography used in Internet protocols
- **OASIS KMIP**: Key Management Interoperability Protocol
- **ETSI SAGE**: Security Experts Group
- **ETSI QSC**: Quantum-Safe Cryptography Industry Specification Group
- **ANSI X9F**: Data and Information Security
  Standards for the financial services industry
- **IEEE P1363**: Standard Specifications for Public-Key Cryptography

# OASIS Key Management Interoperability Protocol (KMIP)


Standards by industry for industry.

# Profile and system specification for post-quantum level

| | |
|---|---|
| Encryption | SHOULD ChaCha20 (with 256-bit key)<br>MAY AES-256 |
| Digital Signature | SHOULD SPHINCS-256 (stateless)<br>SHOULD XMSS (statefull) |
| Key Exchange | SHALL McEliece (with binary Goppa codes using length n = 6960, dimension k = 5413 and adding t = 119 errors). |
| Encryption with Authentication | SHOULD ChaCha20Poly1305 (with 256-bit key)<br>MAY AES-256 (with 96 bit nonce in GCM) |
| Hashes | SHOULD SHA3-384 or SHA3-512<br>MAY SHA-384 or SHA-512 |

KMIP uses the PQCRYPTO initial recommendations.

# Collaboration with CRYPTSOFT


(Card is preview of demo at RSA Conference 2018).

# Selected SDO Activities: NIST

- Workshop on cybersecurity in a post-quantum world, April 2015
  - PQCRYPTO talk for introducing the EU project
  - PQCRYPTO presented several other papers
- Call for "quantum-resistant cryptographic algorithms for new public-key crypto standards"
  - PQCRYPTO was continuously contributing to the discussion of the final evaluation criteria, submitting tens of formal comments
- Submissions to call for "quantum-resistant cryptographic algorithms for new public-key crypto standards"
  - 22 of 69 "complete & proper" submissions by PQCRYPTO
- Evaluation phase
  - PQCRYPTO presented attacks on 15 submissions since then, 10 of which are fatal
  - Only one PQCRYPTO submission successfully attacked (not fatal)

# Selected SDO Activities: IETF / IRTF/CFRG

## Post-quantum activities

- Several Internet Drafts on post-quantum cryptography
- Ongoing discussion about post-quantum cryptography
- For now: Limitation to stateful hash-based signatures in CFRG (with later adoption by NIST), for everything else wait for NIST

## RFC by PQCRYPTO

- A. Hülsing, D. Butin, S. Gazdag, A. Mohaisen, J. Rijneveld. "XMSS: Extended Hash-Based Signatures" draft-irtf-cfrg-xmss-hash-based-signatures-12

# Stay tuned for more

- July 2019: Executive summer school in Eindhoven.
- https://pqcrypto.org: Survey site by Daniel J. Bernstein & me.
  - Many pointers: e.g., PQCrypto conference series.
  - Bibliography for 4 major PQC systems.
- PQCrypto 2016 with slides and videos from lectures (incl. winter school)
- PQCrypto 2017
- https://pqcrypto.eu.org: PQCRYPTO EU project.
  - Expert recommendations.
  - Free software libraries (libpqcrypto, pqm4, pqhw).
  - Lots of reports, scientific papers, (overview) presentations.
- https://2017.pqcrypto.org/school: PQCRYPTO summer school with 21 lectures on video + slides + exercises.
- https://2017.pqcrypto.org/exec: Executive school (12 lectures), less math, more overview. So far slides, soon videos.
- https://csrc.nist.gov/projects/post-quantum-cryptography/round-1-submissions: NIST PQC competition.