Hybrid Cryptography

Combining Classical, Quantum and Post-Quantum Mechanisms

Jan Hajný

Brno University of Technology
hajny@vut.cz
https://axe.vut.cz

AXE Group at Brno University of Technology

Applied Cryptography and Security Engineering (AXE):

- based in Brno, Czech Republic,
- focused on PQC, PETs, Lightweight Crypto, SCA,
- delivering implementations for specific platforms: FPGA, smart-cards, constrained devices.

Quantum Computing

IBM:

- 2023: IBM Eagle: 127 qubits,
- 2024: IBM Heron: 133 (399) qubits, error mitigation,
- 2025: IBM Flamingo: 156 (1092) qubits, error mitigation.

Google:

- 2019: Sycamore: 53 qubits,
- 2024: $5 mil. prize for actual use.

Anhui Research Center (China):

- 2024: Origin Wukong: 72 qubits,
- was available online (to all).

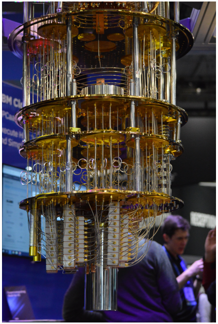


Figure: IBM Quantum Computer.

Quantum Computing - Security Threat I

Schor's Algorithm

- quantum algorithm developed in 1994,
- can be used for fast factorization, i.e. finding p, q for input $n = pq$, and for computing discrete logs,
- runs in polynomial time, i.e. $\log(n)$.

Grover's Algorithm

- quantum algorithm developed in 1996,
- can be used for fast unstructured search, i.e. finding input to blackbox function that produce certain output,
- runs with low complexity of $\sqrt{(}n)$, where n is the size of the function domain.

Quantum Computing - Security Threat II

Asymmetric Cryptography

- Key Agreement Protocols: (EC)**DH** based on discrete logarithm hardness *assumption*,
- Digital Signatures: RSA, (EC)**DSA** based on factoring, discrete logarithm hardness *assumption*,
- Encryption: **ElGamal** based on discrete logarithm hardness *assumption*.

Symmetric Cryptography

- block ciphers based on search complexity.

Advanced Cryptography

- Σ-protocols for ZK proofs: based on discrete logarithm hardness *assumption*,
- ...

Legislation, Recommendations

"As a consequence of quantum vulnerabilities of approved algorithms, it is necessary to replace them with a suitable quantum-resistant cryptography in the not too distant future." NÚKIB

National Authorities

- NUKIB (Czechia): Minimum Requirements for Cryptographic Algorithms
- NSA (US): Commercial National Security Algorithm Suite 2.0
- BSI (Germany): Quantum-safe cryptography – fundamentals, current developments and recommendations
- ANSSI (France): ANSSI views on the PQC transition
- NCSC (UK): Next steps in preparing for PQC

Standardization Bodies

- NIST: Post-Quantum Cryptography Standardization

Solutions: QKD

Quantum Cryptography: Quantum Key Distribution

- known since 1980s, based on quantum physics,
- no hardness assumptions, unconditionally secure (in theory),
- existing solutions: Toshiba, ID Quantique, . . . ,
- massively supported by EU: EuroQCI, CZ-QCI, ...

Problems: expensive (ca. $200K for a link), questionable implementation security, solves only key distribution (expansion), not recommended by security agencies as complete solution[1], difficult integration with existing ICT, only minor standardization

. . .

[1] Position Paper on Quantum Key Distribution

Solutions: PQC

Post-Quantum Cryptography

- *easy* integration with existing ICT, no special HW, cheap,
- existing implementations: Open Quantum Safe, . . . ,
- supported by national authorities: UK, US, Germany, France, Sweden, Netherlands, . . . ,
- standardization candidates ready: CRYSTALS-Kyber, CRYSTALS-Dilithium, FALCON (lattice-based) and SPHINCS+ (hash-based)

Problems: still based on (QC-safe) hardness assumptions, more complex.

Solutions: Hybrid Cryptography and Agility

Hybrid Cryptography

- combines different approaches: QKD, PQC, Classical cryptography,
- secure if some approach fails,
- recommended by some authorities: BSI, ANSSI, . . . , but not NSA,
- valid at least for the transition period,
- relevant also for combining multiple PQC families.

Cryptographic Agility

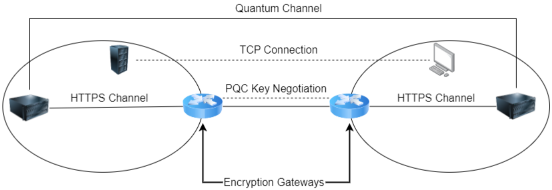
- design that allows simple and quick algorithm replacement.

Problems: slower, larger, easier for KEM, harder for signatures, more space for mistakes.

Experiments: Open-Source Quantum-Safe Encryptor I

CHESS Project Activity: Quantum-Safe Encryptor

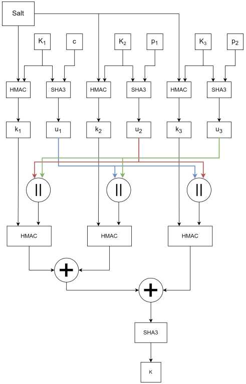
- aim: verify long-distance deployment of a quantum-safe channel,
- based on combination of classical, QKD and PQC,
- deployed between Czechia (Brno - Brno University of Technology) and Estonia (Tartu - Cybernetica),
- based on Linux, publicly available at: https://github.com/gabsssq/Linux-network-traffic-encryptor



Experiments: Open-Source Quantum-Safe Encryptor II

CHESS Project Activity: Quantum-Safe Encryptor

- Classical cryptography: ECDH-512,
- Quantum Key Distribution: IDQ Clavis 3,
- Post-Quantum: CRYSTALS-Kyber 768,
- Payload Encryption: AES-256-GCM,
- Key Combiner: own[2].

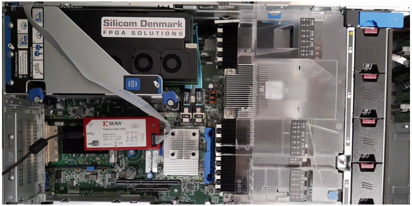


[2]S. Ricci et Al, "Hybrid Keys in Practice: Combining Classical, Quantum and Post-Quantum Cryptography," in IEEE Access, vol. 12, 2024.

Experiments: FPGA Quantum-Safe Encryptor I

NESPOQ Project Activity: FPGA Quantum-Safe Encryptor

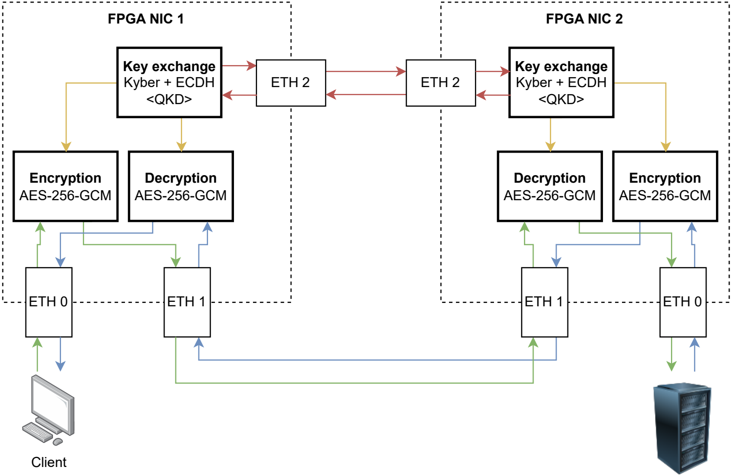
- aim: hardware-accelerate high-speed encryptor for 100 GbE networks using standard TCP/IP protocols,
- based on combination of classical, QKD and PQC - similar to software-based encryptor,
- supported by the Ministry of Interior of Czech Republic, project NESPOQ #VJ01010008 [3],
- implemented on NIC as firmware,
- available also as IP cores.



[3] https://www.nespoq.cz

Experiments: FPGA Quantum-Safe Encryptor II

NESPOQ Project Activity: FPGA Quantum-Safe Encryptor

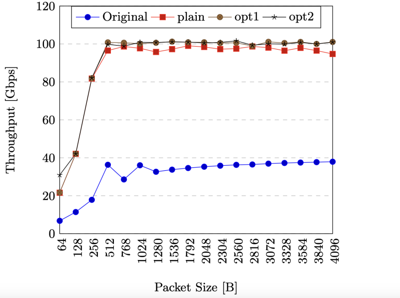


Experiments: FPGA Quantum-Safe Encryptor III

NESPOQ Project Activity: FPGA Quantum-Safe Encryptor

Challenges:

- limmited resources: LUTs, Flip Flops, 200 MHz frequency.
- high throughput: 100 Gbps.
- no existing implementations on FPGAs in VHDL language.
- high parallelism (for AES-GCM).

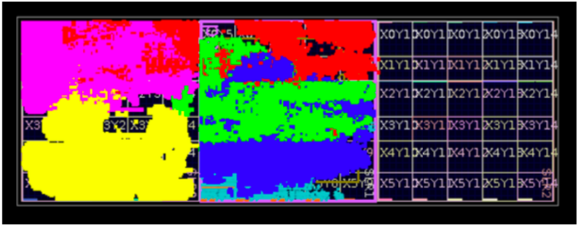


Experiments: FPGA Quantum-Safe Encryptor IV

NESPOQ Project Activity: FPGA Quantum-Safe Encryptor

Components placement after the implementation phase (two out of the three SLRs used):

- yellow - Encryption subcore
- pink - Decryption subcore
- green - Key Exchange
- red - ETH; blue - PCI-E



Conclusions and Provocative Questions

Simple Conclusions:

- Transition to quantum-safe is a must (due to *store and decrypt later* attacks).
- PQC is closer to practical deployment than QKD.
- Concrete algorithms depend on standards and authority recommendations: coming 2024/2025.
- Integration with existing infrastructure is a bigger issue than cryptographic algorithms.
- Agility and hybrid approach is highly advisable.

Provocative questions:

- Will *ever* be quantum computer constructed?
- Are current QCs even close to some *practical use* in cryptography? (noise, stablity, number of logical qubits...)
- Are lattice-based algorithms, i.e. CRYSTALS, *secure*[4]?

[4] Yilei Chen, *Quantum Algorithms for Lattice Problems*, https://eprint.iacr.org/2024/555

Thank you for your attention.

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