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Integrating Post-Quantum Cryptography into Existing Systems Today

CHESS

Cyber-security Excellence Hub in Estonia and South Moravia

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[All references are in the form of clickable links]

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Presentation outline

- **Introduction**
- **Current state of PQC**
  - Libraries, ASN.1, JSON Web Algorithms, Hybrid modes
- **General implementation challenges**
  - Relevant locations, technological constraints, implementation in the codebase
- **Practical results, remarks, and examples**
  - PQ authentication framework, PQ-CDOC2, PQ-IVXV
- **Conclusions**

Introduction

- **Standardization** of PQC (Post-Quantum Cryptography) is *only* the **first step in a long process of actual deployment** in real-life IT systems
- Challenge:
  - Rolling out PQ support in all system and architecture layers
  - While ensuring functionality, compatibility, interoperability (and security)
- Our work:
  - Focus on engineering aspects of PQ protocol implementations
  - Exploring current options
  - Remarks and tips

Current state of PQC

Libraries, ASN.1, JSON Web Algorithms, Hybrid modes

PQ Libraries

- PQClean (C)
  - aggregates NIST-submitted algorithms with unified API
- libOQS (C)
  - higher-level library (provides submitted algorithms until NIST round 4)
  - wrappers for C++, Python, Java, Go, .NET, and Rust
  - applications built with libOQS (OpenSSL, OpenSSH, OpenVPN forks)
- libpqcrypto (C)
  - similar to libOQS, not maintained anymore? (last update in 2018)
- BouncyCastle (Java), rustpq/pqcrypto (Rust), pqm4 (C, Cortex-M4)

PQ ASN.1 structures

- Essential for PQ-X509, but also used in other applications
- No standards exist yet - NIST requires raw bytes
- Multiple RFC drafts for specific PQ algorithms
  - private and public keys with specific attributes/parameters
  - e.g. `DilithiumPrivateKey` (contains `nonce`, `tr`, `s1`, `s2`, `t0`, etc.)
- Differences in PQ libraries
  - e.g. *libOQS* returns raw bytes, *BouncyCastle* returns proposed ASN1 objects
- PQ Object Identifiers (OIDs): OQS defined their own, BouncyCastle expanded with KEMs

PQ JSON Web Algorithms (RFC 7518)

- Usage: *JW Signature*
- Sig. format: *(DIGSIG + HASH identification)*
- Example: *"ES384" means "ECDSA using P-384 curve and SHA-384"*
- No RFC drafts for PQ JWAs, but there is RFC draft for PQ JW Encodings:
  - e.g. *CRYDI5 = CRYSTALS-Dilithium parameter set 5*
  - only DIGSIG identification, no HASH?
    - *always use SHA512?*
    - *CRYDI5-256/384/512?*
    - *wait for another RFC?*

Hybrid mode (PQ + classic crypto)

- Post-Quantum cryptography:
  - ensures the longevity of data protection
- Classical cryptography:
  - protects against emerging threats on unexplored PQC
- Most common modes:
  - concatenation, sequential
  - both can have their issues → nothing concrete yet
  - *Ghinea et al.* propose novel method to improve unforgeability of hybrid dig. sig. when using ECDSA

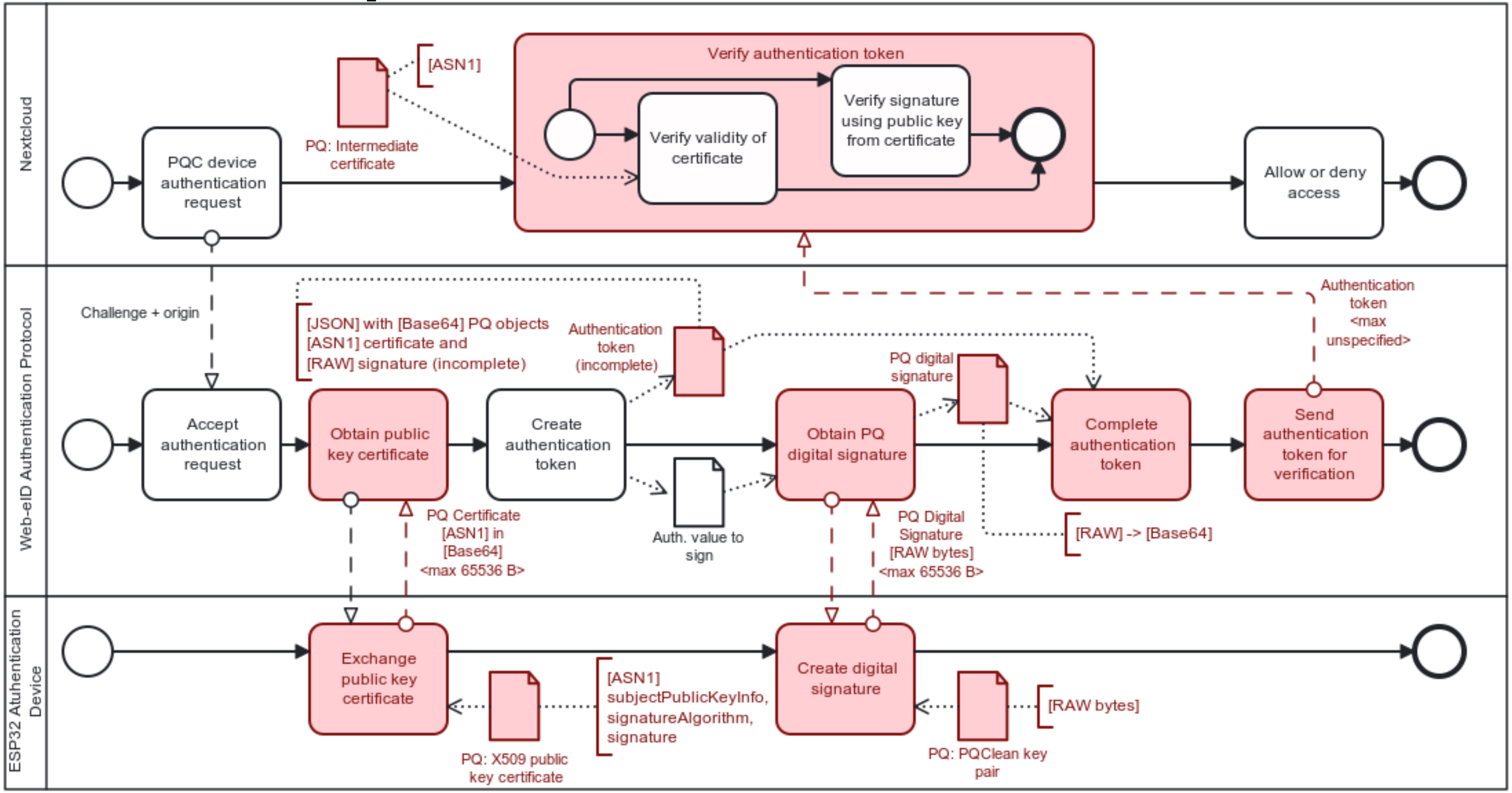
General implementation challenges

Relevant locations, technological constraints, implementation in the codebase

Identifying relevant locations

- First step in implementing PQC in an existing application
- **Identify all PKI** (public key infrastructure) **objects from the start of their lifetime** to their ends
  - helps to understand the extent of required changes
- **Beware of MTU** (Maximum Transmission Unit) when transferring PKI objects between different system components
  - bigger objects, variable size (Falcon)
- **Beware of changing data formats** (ASN1, Base64, PEM, ...) between components

BPMN example



Technological constraints

- Assess the technological and computational **boundaries of the current system**
  - Increased **performance**, **memory**, and **storage overhead**
  - Limited devices and slow networks
- Protocol adjustment examples:
  - streaming public keys and signatures into the limited memory of a HSM component
  - use key encapsulation instead of digital signatures
  - allocate all objects in heap instead of limited stack memory (our case)

Implementing PQ algorithms in the codebase

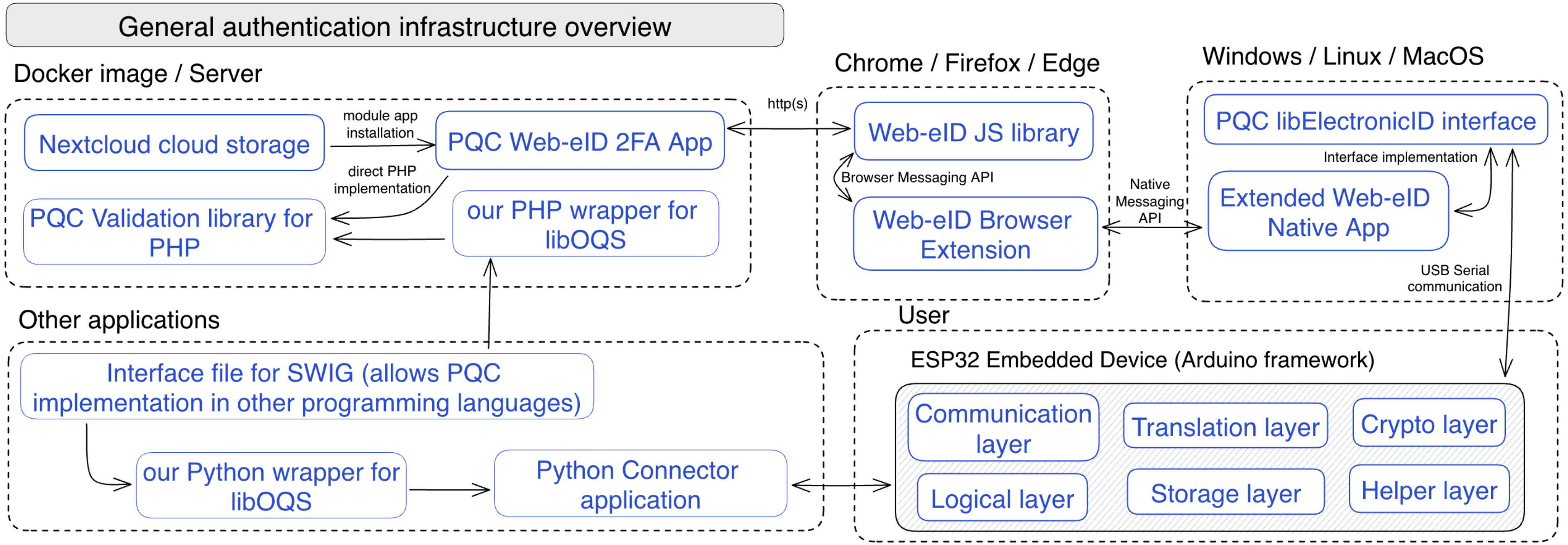
- Start at the **beginning of the data lifecycle**
- Implement post-quantum support **one step at a time**
- **Extensions or complete swaps** of cryptographic libraries might be required
  - if not available, create your own using SWIG
- Expect future changes - standardization is not over!

Practical results, remarks, and examples

PQ authentication framework, PQ-CDOC2, PQ-IVXV

Project: PQ Authentication Framework (PoC)

- Nextcloud cloud storage + Web-eID + embedded device
  - authentication result based on Dilithium5 or Falcon1024 signatures
  - multiple low-level PQ-capable components



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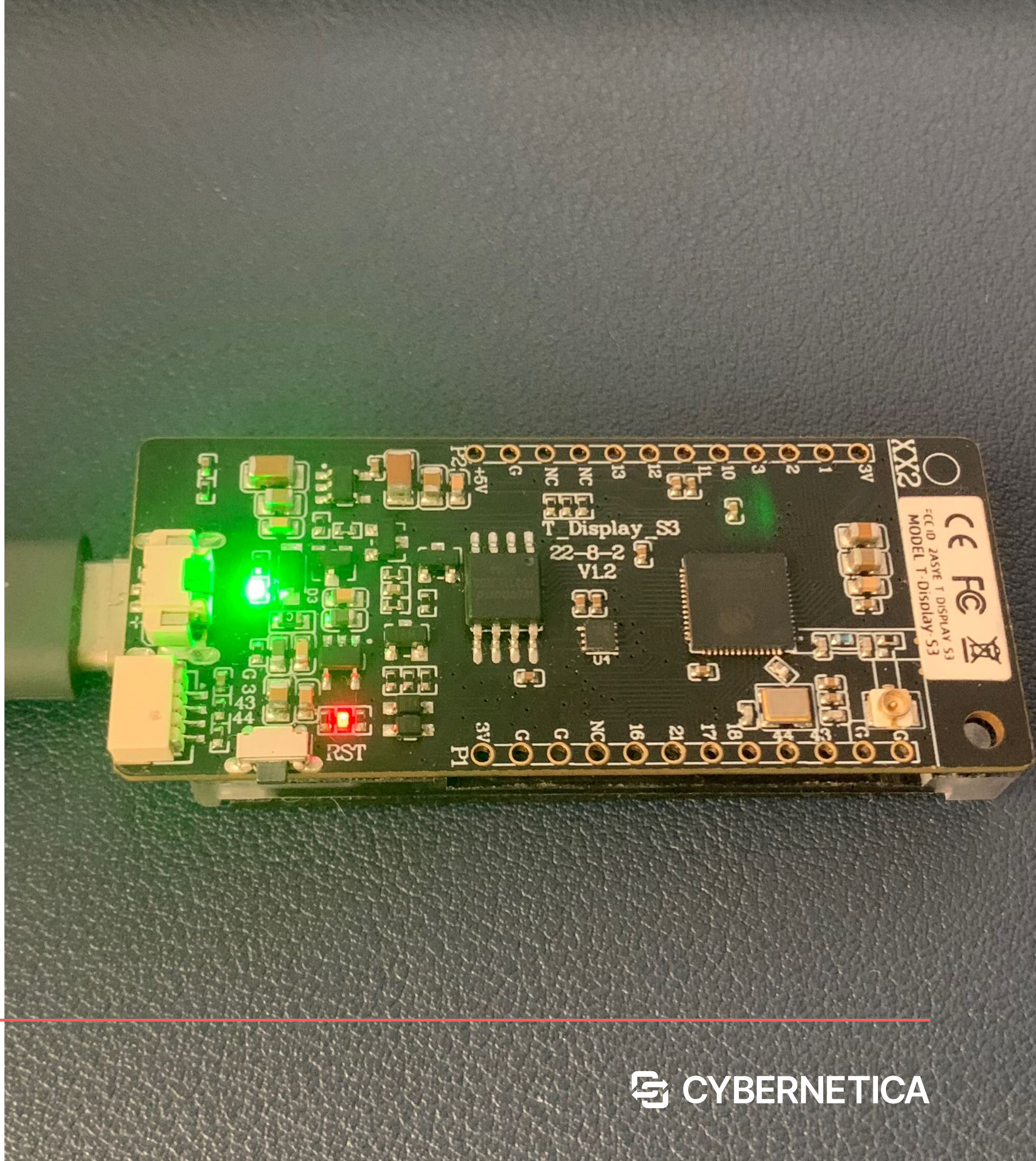
Embedded devices

- Smart cards are not suitable yet(?)
  → LilyGO T-Display-S3
- Problematic memory management:
  - Limited to 8 KB of stack RAM
  - *PQClean* allocates to a stack a lot
- Solved by adjusting *PQClean* code by using:
  - `malloc` and `free` functions
  - `std::unique_ptr` (C++ v11)



libOQS extensions

- Available wrappers for C++, Python, Java, Go, .NET, and Rust
  - ~~PHP~~? → SWIG wrapper generator!
- C/C++ interface definition required
  - → *liboqs-php*, *liboqs-python*
- Some remapping was required:
  - PHP's `string` + Python's `bytearray` into C++'s `uint8_t*`
  - and vice versa

PQ in PHP

- **OpenSSL usage → OQS-OpenSSL**
  - v1.1 fork with built-in functions:
    - complicated installation, PHP rebuild required
    - built-in functions have only DSA, DH, RSA, and EC hardcoded
  - v1.1 fork with command execution using `exec()`, `system()`, etc.:
    - works, but is not practical
  - v3 extension provider with combined usage (recommended):
    - extends regular OpenSSL@3
    - some built-in functions do not require algorithm identifier (e.g. `openssl_verify()`)
- **PHPSecLib → our PQC-PHPSecLib fork**
  - uses *OQS-OpenSSL* or *liboqs-php* (based on availability)

Project: PQ-CDOC2

- **CDOC2** = new version of *Encryption DigiDoc Format* (in development)
  - specification defining the process of **securing and exchanging encrypted messages**, similar to CMS (Cryptographic Message Syntax)
  - reference implementation in Java (uses BouncyCastle)
  - expects RSA, EC or symmetric keys
- **PQ-CDOC2** = CDOC2 expanded to accept **CRYSTALS-Kyber keys**
  - updated version of BouncyCastle to include PQ algorithms (v1.74)
  - expanded the codebase by following RSA/EC objects

PQ in BouncyCastle

- Not well documented
- `org.bouncycastle.pqc.*` packages
- Works with actual algorithm parameters from ASN1 drafts
  - vs raw bytes in libOQS
  - e.g. `KyberPublicKeyParameters` has `t` and `rho`

```
static {
    java.security.Security.addProvider(
        new org.bouncycastle.pqc.jcajce.provider.BouncyCastlePQCProvider()
    );
}
```

PQ in BouncyCastle

```java
public static AsymmetricCipherKeyPair generateKeyPair(KyberParameters params) throws
NoSuchAlgorithmException {
    KyberKeyPairGenerator kpGen = new KyberKeyPairGenerator();
    kpGen.init(new KyberKeyGenerationParameters(Crypto.getSecureRandom(), params));

    return kpGen.generateKeyPair();
}

SubjectPublicKeyInfoFactory.createSubjectPublicKeyInfo(
    (KyberPublicKeyParameters) kpGen.getPublic()
);

PrivateKeyInfoFactory.createPrivateKeyInfo(
    (KyberPrivateKeyParameters) kpGen.getPrivate()
);
```

PQ in BouncyCastle

```java
public static SecretWithEncapsulation kyberEncapsulate(KyberPublicKey kyberPublicKey)
        throws GeneralSecurityException {
    try {
        KyberPublicKeyParameters keyParams = (KyberPublicKeyParameters) PublicKeyFactory
                .createKey(kyberPublicKey.getEncoded());

        KyberKEMGenerator kem = new KyberKEMGenerator(Crypto.getSecureRandom());
        return kem.generateEncapsulated(keyParams);
    } catch (IOException | NoSuchAlgorithmException e) {
        throw new GeneralSecurityException(e);
    }
}
```

PQ in BouncyCastle

```java
public static byte[] kyberDecapsulate(byte[] encapsulation, KyberPrivateKey
kyberPrivateKey)
        throws GeneralSecurityException {
    try {
        KyberPrivateKeyParameters keyParams = (KyberPrivateKeyParameters)
PrivateKeyFactory
                .createKey(kyberPrivateKey.getEncoded());

        KyberKEMExtractor kem = new KyberKEMExtractor(keyParams);
        return kem.extractSecret(encapsulation);
    } catch (IOException e) {
        throw new GeneralSecurityException(e);
    }
}
```

PQ-CDOC2: key-server scenario

- Scenario with key exchange server ensures:
  - possibility of decrypting only once even after private key compromise
  - possibility of encrypted message's expiry date
- Scenario requires:
  - public key **in TLS client certificate** == public key of a recipient **in encrypted message**
  - i.e. client needs to provide a valid certificate, where **subjectPublicKeyInfo is a KYBER key** = problem in current Java SSL implementation
- Solution:
  - use X509 extension `id-ce-subjectAltPublicKeyInfo (2.5.29.72)`

PQ Java Keytool

- keytool = command for managing a keystore of cryptographic objects
- PQ BouncyCastle → PQ Java Keytool
- e.g. to generate .p12 with Dilithium keypair and self-signed certificate:

```
keytool \
    -providerpath bcprov-jdk18on-175.jar \
    -provider org.bouncycastle.pqc.jcajce.provider.BouncyCastlePQCProvider \
    -genkeypair \
    -keyalg Dilithium5 \
    -alias cdoc20-client-pqc-CA \
    -keystore cdoc20clientpqcCA.p12 \
    -storepass passwd \
    -sigalg Dilithium5 \
    -dname "CN=cdoc20-client-pqc-CA,OU=ISRI,O=CyberneticaAS,L=Brno,S=Czechia,C=CZ"
```

Project: PQ-IVXV (El. voting scheme)

- Quite a challenge ahead of us:
  - ensure quantum-safety of electronic voting process
- Will require PQ versions of **more advanced cryptographic primitives**
  - vote encryption, mix-nets, ZK proofs
- Current implementation is written in:
  - Java (pure implementations of ElGamal → new dependency?)
  - Go (CIRCL Library?)
- New project-specific scheme will be probably required for vote encryption (we can't use standard KEM algorithms)

Conclusions

- Implementing PQC today is **possible, but complicated**:
  - different libraries → different approaches
  - not well documented
  - computational constraints
  - standardization is not finished
- But it is definitely **worth a try**!
  - all quantum-computer **timelines are** (most probably) **estimates**
  - better to be **prepared and safe** than **sorry and late** ;)
- There is big space for **open-source PQ contributions**

References

For developers and engineers:

- links in presentation slides
- PQ Authentication Framework (all components)
- OQS-OpenSSL in PHP remarks (documentation)
- PQ-CDOC2: currently in private development repo, may appear in official one some day, contact me for more details

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