Post-Quantum

Cryptography Conference

# Real-World Readiness for PQC: Gaps, Gains, and Groundwork

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PKI Consortium

Real-world Readiness

# Post-Quantum Cryptography

**Tomas Gustavsson**
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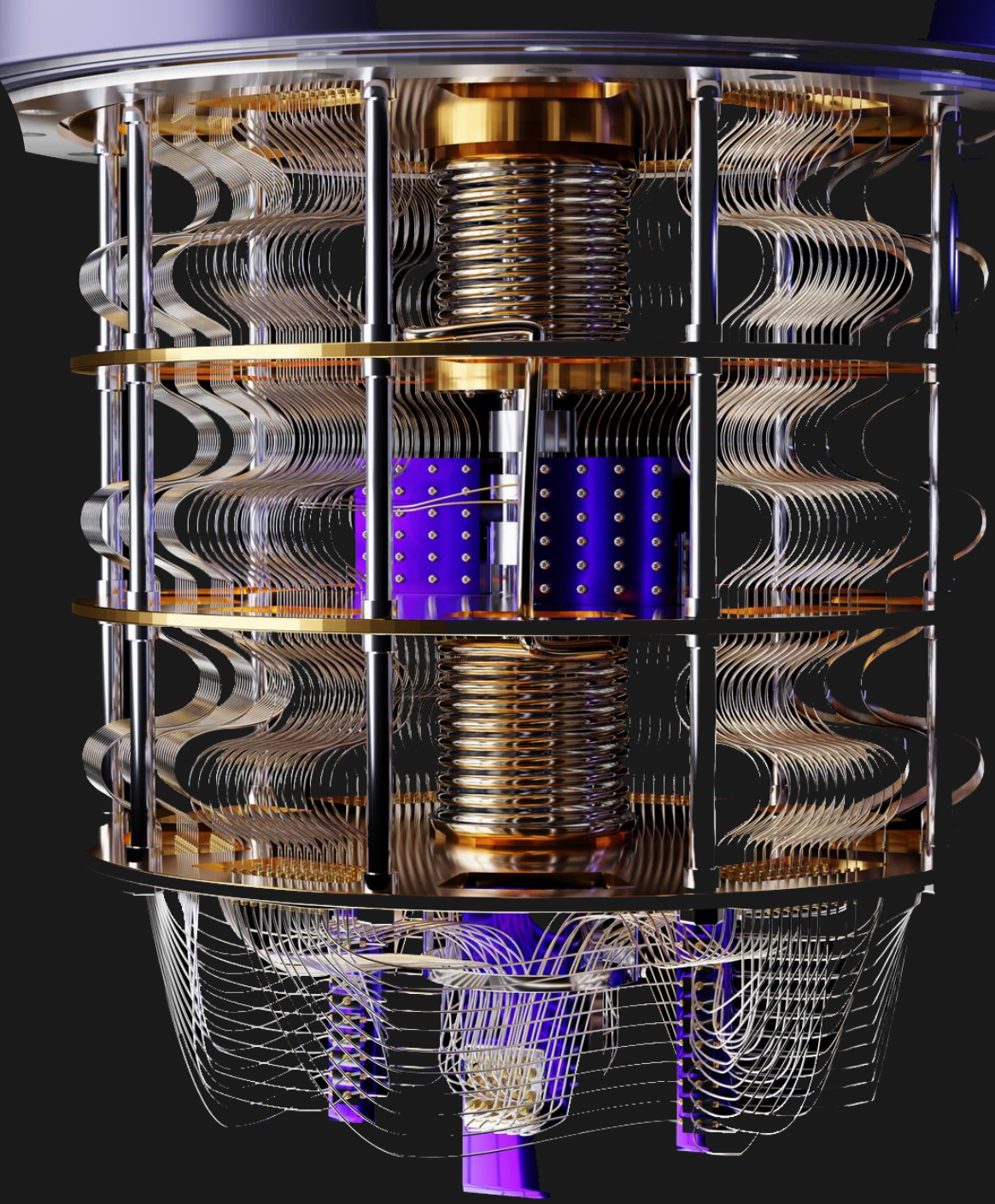

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~~Dilithium~~

ML-DSA / FIPS 204

~~Kyber~~

ML-KEM / FIPS 203

~~SPHINCS+~~

SLH-DSA / FIPS 205


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# Steps to Quantum Readiness

**Many companies are around here but can't progress until vendors/regulations are ready.**

## 01 Inform

- Engage senior stakeholders
- Bring "comparison problem" like Y2K
- Budget requires buy-in

**Talk to your vendors!**
Assess the quantum-readiness of technology vendors and supply chain partners

## 02 Discover

- Initial mapping of critical crypto assets
- Catalog by algorithm, dependency and expiry
- Prioritize by risk: High, Med, Low

## 03 Automate Discovery

- Replace manual processes with automated workflows
- Build a foundation for migration at scale
- Inventory is CONTINUOUS

## 04 Test

- Introduce hybrid certificates
- Purge weak/outdated crypto
- Start testing quantum-resistant TLS

## 05 Upgrade

- Upgrade your infrastructure (HSM, KMS, CLM, PKI, signing, libraries)
- Phase out CAs incompatible with PQC algos

## 06 Deploy

- Begin to implement NIST
- PQC algorithms into production based on your prioritization

## 07 Manage

- Continuously monitor and manage your enterprise cryptography through policy and automated processes

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# Standards

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# September 2025 Heatmap: Current State of PQC Standards and Adoption

Source: https://pqcc.org/, October 1, 2025

https://pqcc.org/international-pqc-requirements/

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## Heatmap

| Standard | Overall Range | Pure PQC encrypt | Hybrid PQ encrypt | Pure PQ sig | Hybrid PQ sig |
|---|---|---|---|---|---|
| SSH | 3 to 8 | 3 | 8 | 3 | 3 |
| TLS 1.2[1] | 0 to 0 | 0 | 0 | 0 | 0 |
| TLS 1.3[2] | 3 to 9 | 7 | 9 | 7 | 3 |
| X.509[3] | 4 to 7 | 7 | 4 | 7 | 4 |
| S/MIME | 3 to 7 | 5 | 3 | 7 | 3 |
| OpenPGP | 2 to 4 | 2 | 4 | 4 | 4 |
| IKE/IPSec | 2 to 8 | 8 | 8 | 3 | 2 |
| MLS | 2 to 4 | 4 | 4 | 4 | 2 |
| DNSSec | 1 to 1 | - | - | 1 | 1 |

## Key

| | |
|---|---|
| 0 | Consensus Against Inclusion |
| 1 | Blocked / Stalled |
| 2 | In Progress / Chartered |
| 3 | Active Proposals / Drafts |
| 4 | Progress to Finalization |
| 5 | Finalized / Approved |
| 6 | Integration Progress |
| 7 | Integrated in Libraries |
| 8 | Some Adoption |
| 9 | Broad Adoption |
| - | Unknown / NA |

# Migration?

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# Putting it all together

Firmware Verification

Document Signatures

Secure eMail with S/MIME

Secure Boot

Secure comm with TLS



Certificate Validation (OpenSSL/Bouncy Castle)

ML-DSA Signing

ML-DSA TSA

ML-DSA signature certificate

ML-KEM encryption certificate

ML-DSA Signing

TLS ML-KEM hybrid key exchange

ML-DSA server/ client certificate

OCSP

ML-DSA signature certificate

ML-KEM encryption

ML-DSA CA

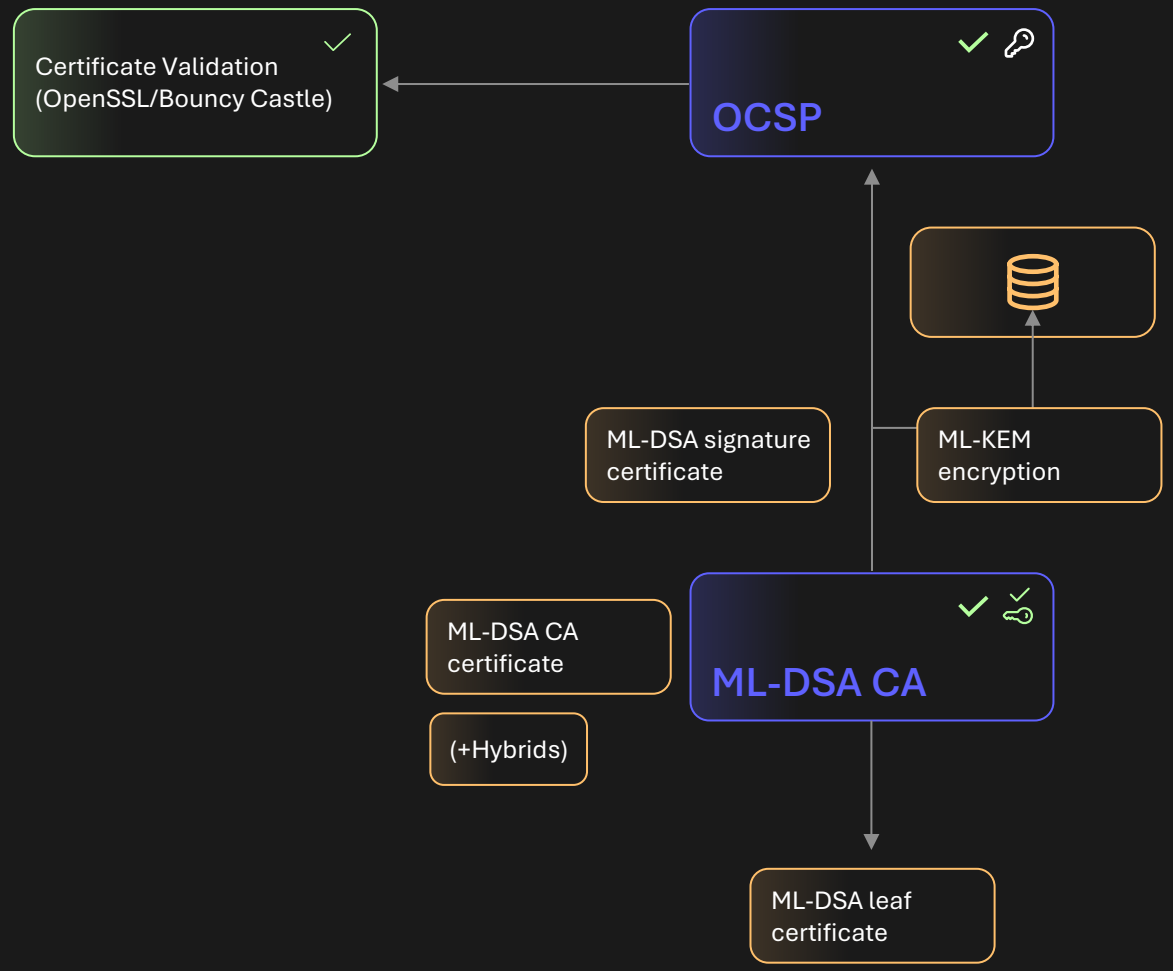
ML-DSA server certificate

ML-DSA CA certificate

Server
Apache / NginX

certbot

# PKI

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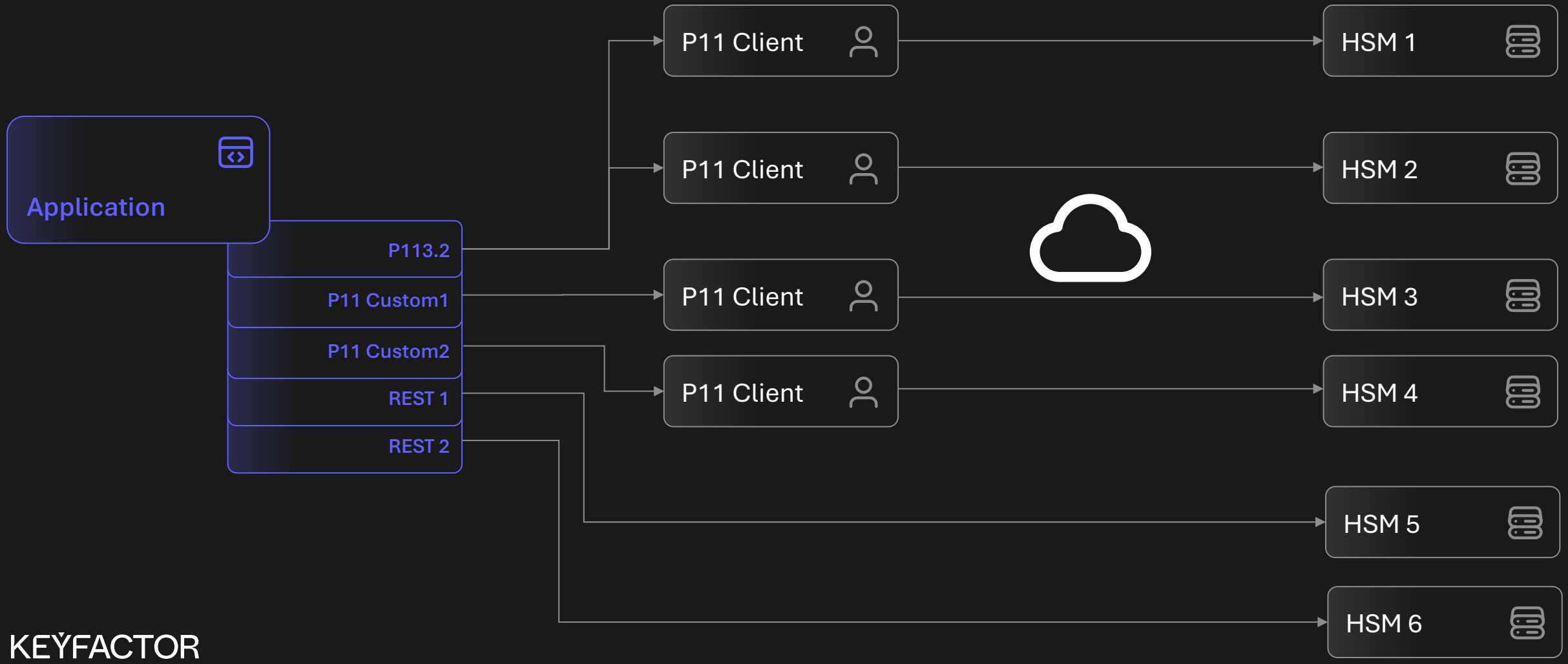
# HSM Integration in Practice

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# PQC
# in Practice


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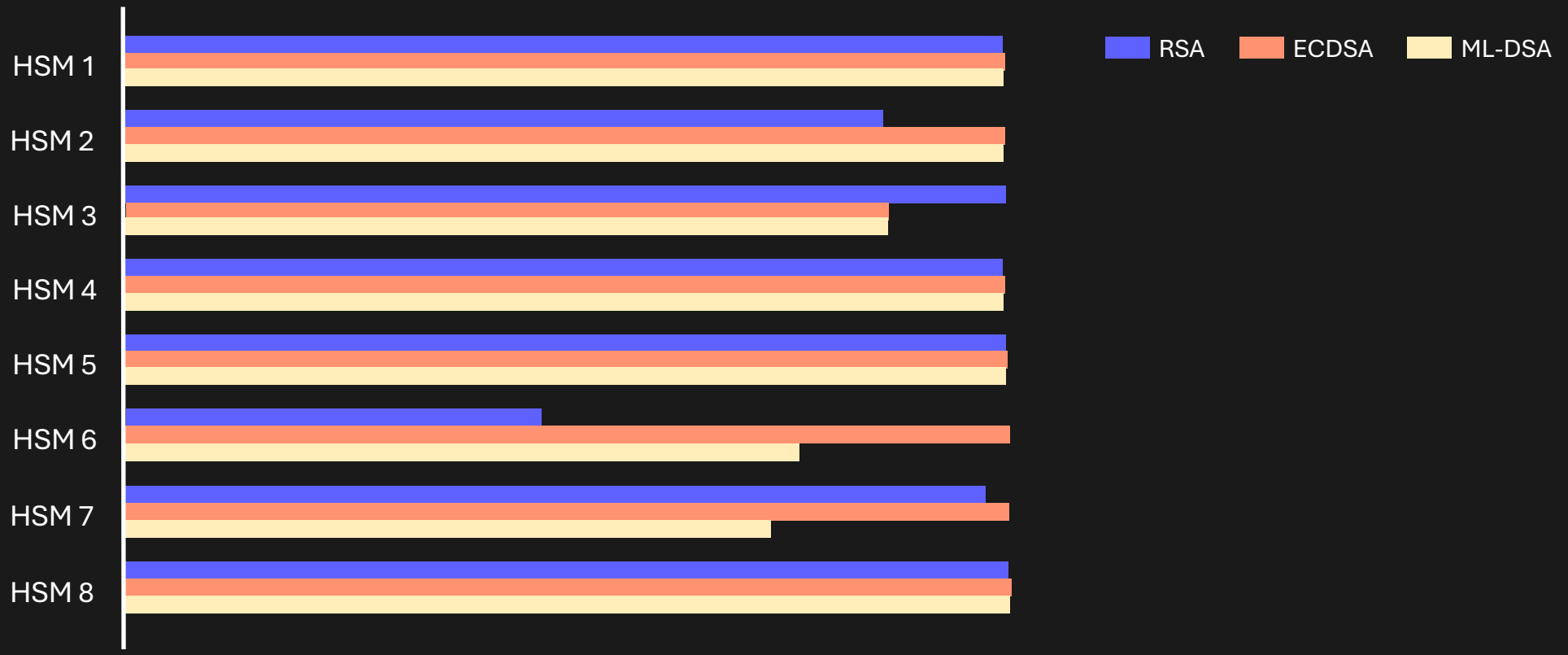
# Certificate/OCSP Performance

## PKCS#11 or REST

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# CRL size limits (ML-DSA)


## Sizes vary

- Certificates are small
- CRLs are small to large
- Bank transactions are small
- Documents are small to medium
- Firmware is large to huge

ExternalMu-ML-DSA saves the day!
(where CMS w/ signed attributes doesn't)

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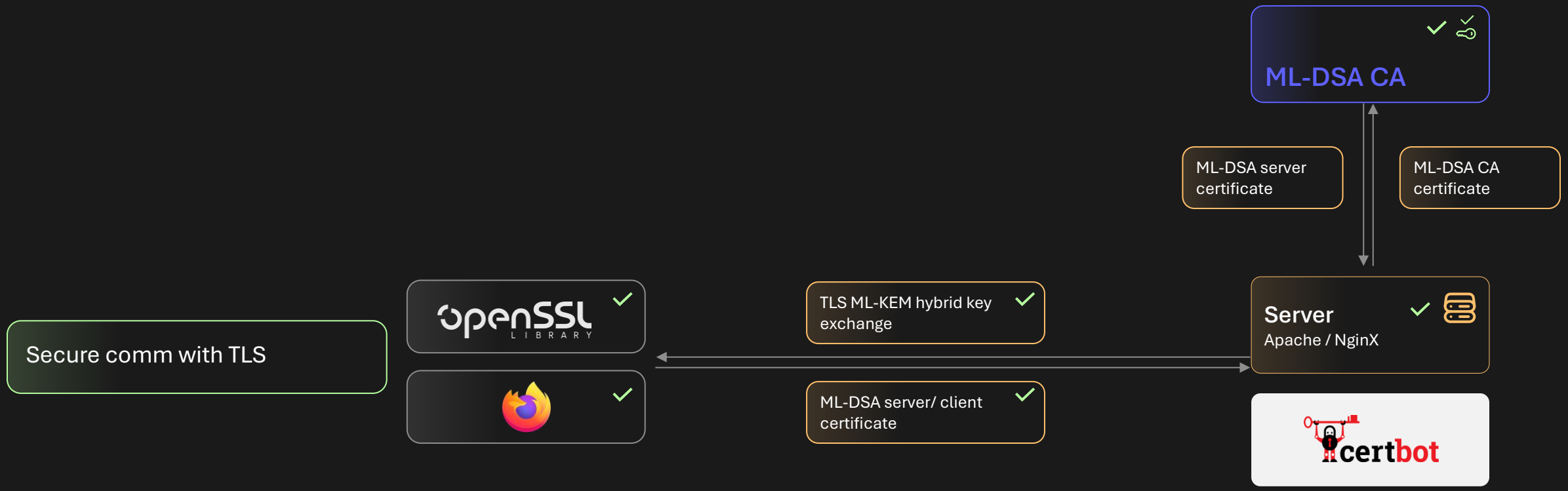
*We want to know your requirements for ExternalMu-ML-DSA – come talk to us*

# TLS


ML-DSA CA
ML-DSA server certificate
ML-DSA CA certificate
Secure comm with TLS
OpenSSL LIBRARY
TLS ML-KEM hybrid key exchange
Server
Apache / NginX
ML-DSA server/ client certificate
certbot

# Off-the-shelf TLS

- Ubuntu 25.10 - OpenSSL 3.5
- RHEL 10 – OQS (test), RHEL 10.1 - OpenSSL 3.5

Red Hat blog →

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- Alpine, CentOS Stream, Debian, SUSE, ...
- Windows Insiders

Microsoft blog →

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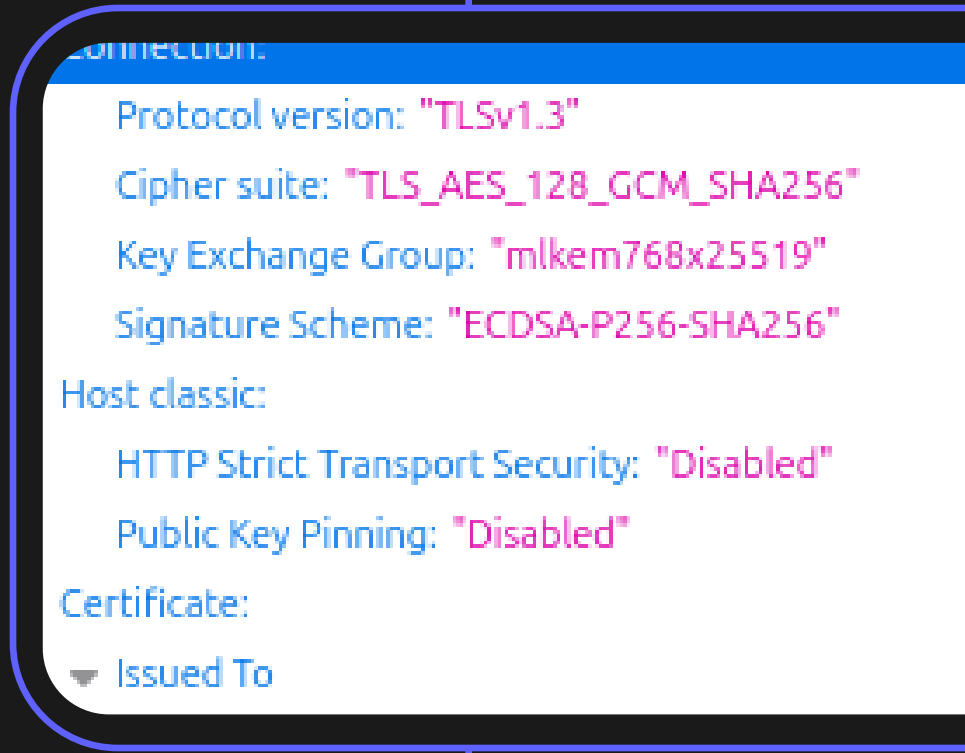
# Off-the-shelf TLS – OK

Ubuntu 25.10 - OpenSSL 3.5

- apt install apache2
- a2enmod ssl

```
<VirtualHost *:443>
    ServerName www.classic.com
    DocumentRoot /var/www/classic
    SSLEngine on
    SSLCertificateFile /home/user/openssl/apache2/classic-cert.pem
    SSLCertificateKeyFile /home/user/openssl/apache2/classic-key.pem
    SSLCertificateChainFile /home/user/openssl/apache2/classic-ca.pem
</VirtualHost>
```

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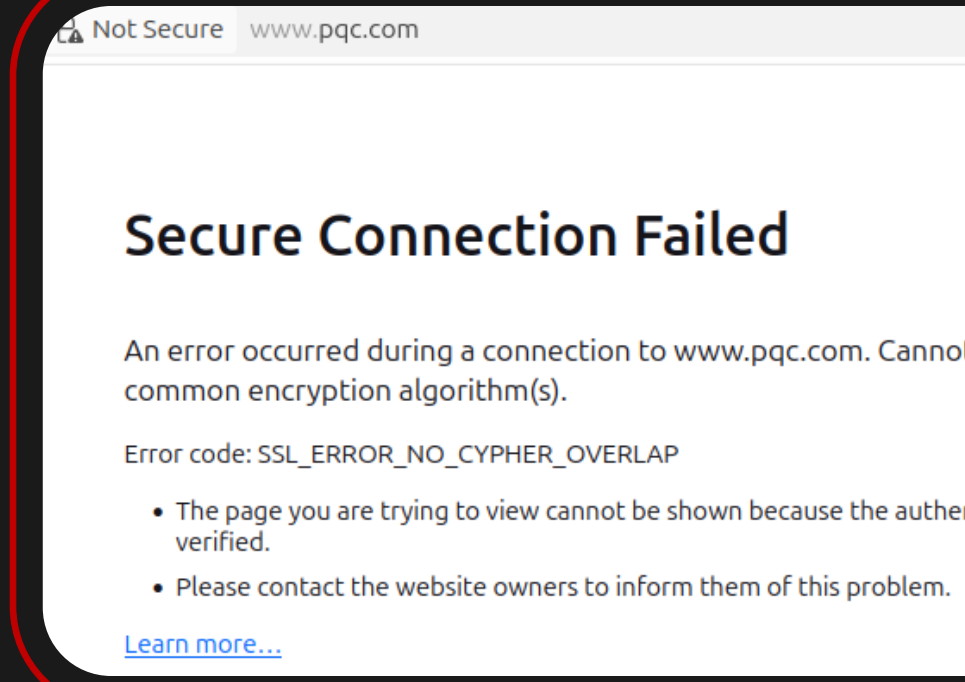
# Off-the-shelf TLS – NOK

Ubuntu 25.10 - OpenSSL 3.5

- apt install apache2
- a2enmod ssl

```
<VirtualHost *:443>
    ServerName www.pqc.com
    DocumentRoot /var/www/pqc
    SSLEngine on
    SSLCertificateFile /home/user/openssl/apache2/pqc-cert.pem
    SSLCertificateKeyFile /home/user/openssl/apache2/pqc-key.pem
    SSLCertificateChainFile /home/user/openssl/apache2/pqc-ca.pem
</VirtualHost>
```

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# Off-the-shelf TLS – OK

```
>openssl s_client -CAfile pqc-ca.pem -connect www.pqc.com:443
```

```
Connecting to 127.0.0.1
CONNECTED(00000003)
depth=1 CN=PQC MLDSA Root
verify return:1
depth=0 CN=pqc
---
Certificate chain
0 s:CN=pqc
   i:CN=PQC MLDSA Root
   a:PKEY: ML-DSA-44, 10496 (bit); sigalg: ML-DSA-44
   v:NotBefore: Aug 18 09:46:28 2025 GMT; NotAfter: May 16
   09:46:27 2026 GMT
```

```
Peer signature type: mldsa44
Negotiated TLS1.3 group: X25519MLKEM768
---
SSL handshake has read 11879 bytes and written 1633 bytes
Verification: OK
---
New, TLSv1.3, Cipher is TLS_AES_256_GCM_SHA384
Protocol: TLSv1.3
Server public key is 10496 bit
Verify return code: 0 (ok)
Post-andshake New Session Ticket arrived:
SSL-Session:
    Protocol  : TLSv1.3
    Cipher    : TLS_AES_256_GCM_SHA384
```

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# Off-the-shelf TLS – OK

```
>apt install curl (8.14.1)

>snap install curl (8.16.0)

>curl --cacert pqc-ca.pem https://www.pqc.com:443 -iv
```

```
* Host www.pqc.com:443 was resolved.
* IPv6: (none)
* IPv4: 127.0.0.1
*   Trying 127.0.0.1:443...
* ALPN: curl offers h2,http/1.1
* TLSv1.3 (OUT), TLS handshake, Client hello (1):
*  CAfile: /home/user/pqc-ca.pem
```

```
* SSL connection using TLSv1.3 / TLS_AES_256_GCM_SHA384 /
  X25519MLKEM768 / id-ml-dsa-44
* Server certificate:
*  subject: CN=pqc
*  subjectAltName: host "www.pqc.com" matched cert's "www.pqc.com
*  issuer: CN=PQC MLDSA Root
*  SSL certificate verify ok.
*   Certificate level 0: Public key type ML-DSA-44 (10496/128
  Bits/secBits), signed using ML-DSA-44
*   Certificate level 1: Public key type ML-DSA-44 (10496/128
  Bits/secBits), signed using ML-DSA-44
* Connected to www.pqc.com (127.0.0.1) port 443
```

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# Off-the-shelf TLS – OK

```
>openssl req -newkey ML-DSA-44 -out mldsa.csr

>sudo certbot certonly --server
https://ejbca.example.com:8442/ejbca/acme/directory -d
www.pqc.com --apache --agree-tos --email
admin@example.com --no-eff-email --csr mldsa.csr --dry-
run



>certbot --help security

...

--key-type {rsa,ecdsa}
```

certbot

## View Certificates

| | |
|---|---|
| **Username** | **iUJ600rF6c7rRQURTqco53UJv3_bsvIpyxwBC7fOaDQ** |
| Certificate number | 1 of 1 |
| Certificate Type/Version | X.509 v.3 |
| Certificate Serial Number | 37B5DE67C0794D1E2240937B7C182CE63E0A5F16 |
| Issuer DN | CN=PQC MLDSA Root |
| Valid from | 2025-08-22 16:51:52+02:00 |
| Valid to | 2026-08-22 16:51:46+02:00 |
| **Subject DN** | **CN=www.pqc.com** |
| Subject Alternative Name | |
| Subject Directory Attributes | None |
| Public key | ML-DSA-44 (128 bits): EB4019044694B70A7E7B511011D95522B438174470FFFDC... |
| Alternative Public key | - (-): - |
| **Basic constraints** | **End Entity** |
| Key usage | Digital Signature |
| Extended key usage | Client Authentication,Server Authentication |
| Name constraints | No |
| Authority Information Access | No |
| Qualified Certificates Statements | No |
| Certificate Transparency SCTs | No |
| Signature Algorithm | ML-DSA-44 |
| Alternative Signature Algorithm | - |
| Fingerprint SHA-256 | CBC28576B5C095AC7D5972927D78C015 3A723EE6DB4E2050408778D0670EA322 |
| Fingerprint SHA-1 | 07AFC8653463C52834D0D88B256B6E3239C07505 |
| Revoked | No |

Republish | Unspecified | Revoke

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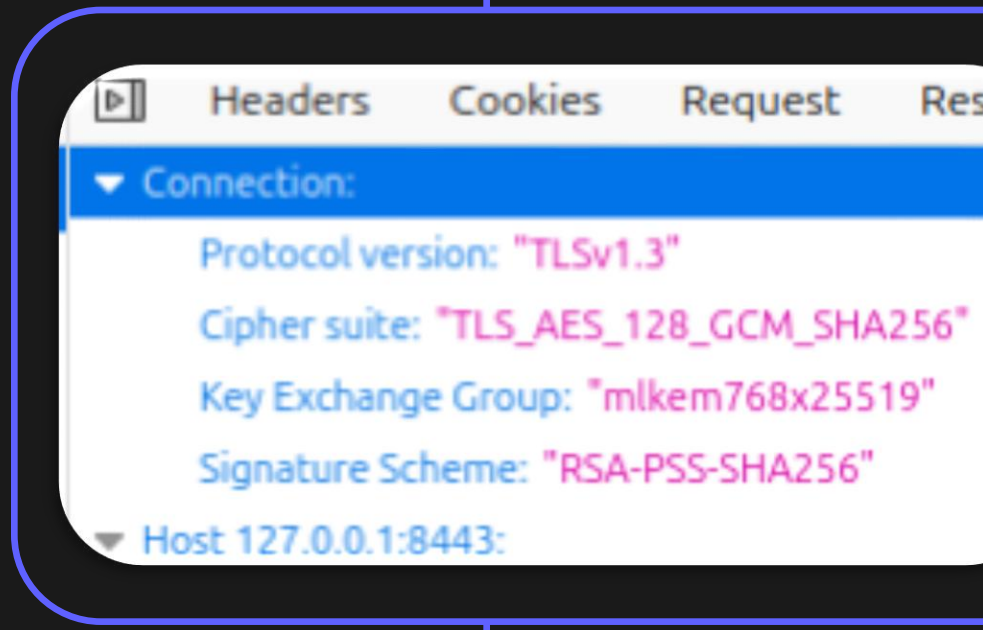
# Off-the-shelf TLS – OK

```
>vim /usr/lib/jvm/java-17-openjdk-amd64/conf/security/java.security
```

```
security.provider.1=BC
security.provider.2=BCJSSE BC
```

```
>vim /opt/wildfly/bin/standalone.conf
```

```
JAVA_OPTS="$JAVA_OPTS --module-path=/opt/bc-module-jars"
```

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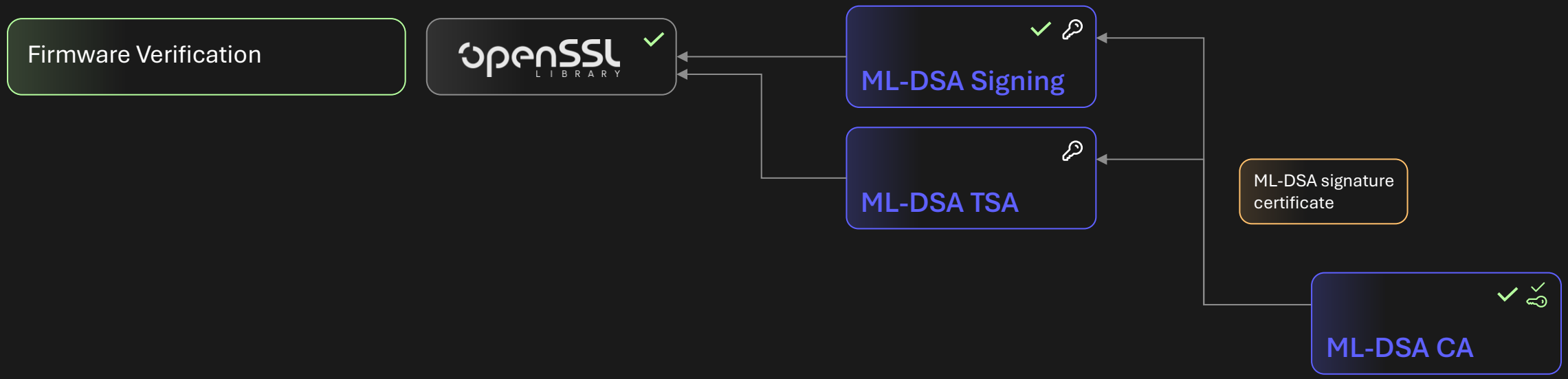
# Signing

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# Off-the-shelf CMS

CMS

- attached or detached signatures
- signed or unsigned attributes

```
CMSSignedDataGenerator gen = new CMSSignedDataGenerator();
final ContentSigner signer = new
JcaContentSignerBuilder(ML-DSA).build(private);
```

```
> openssl cms -verify -in something-to-sign.txt-
  detached.p7s -inform DER -CAfile
  MLDSA44.cacert.pem -content something-to-
  sign.txt -binary
Here is something to sign
CMS Verification successful
```


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# Stumbling blocks

## Time Stamping

```
TimeStampResponseGenerator tsRespGen = new TimeStampResponseGenerator(tsTokenGen,
  TSPAlgorithms.ALLOWED);
  TimeStampResponse tsResp = tsRespGen.generate(request, new BigInteger("23"), new
  Date());
  byte[] tsrBytes = tsResp.getEncoded();
```

```
> openssl ts -verify -in test.tsr -data test.txt -CAfile TSA.cacert.pem
Verification: FAILED
80AB6C2187720000:error:1780006D:time stamp
  routines:TS_RESP_verify_signature:signature
  failure:crypto/ts/ts_rsp_verify.c:148:
```

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# Stumbling blocks

Compliance

- draft-ietf-lamps-cms-ml-dsa – SHA-2, SHA-3, SHAKE
- CNSA 2.0 profile – SHA-2
- Default(ed) to digest algorithm used in signature (SHAKE for ML-DSA, SHA512 for SHA512WithRSA… – all variant work  but CNSA compliance may be a thing

```
CMSSignedDataGenerator gen = new CMSSignedDataGenerator();

final ContentSigner signer = new JcaContentSignerBuilder(ML-DSA).build(private);

final JcaDigestCalculatorProviderBuilder dbuilder = new JcaDigestCalculatorProviderBuilder();

final JcaSignerInfoGeneratorBuilder sbuilder = new
  JcaSignerInfoGeneratorBuilder(dbuilder.build());

→ sbuilder.setContentDigest(new AlgorithmIdentifier(digestAlgOID));
```

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# Stumbling blocks

```
>openssl cms -sign –nodetach –outform DER -in msg.txt -out out.msg -
 signer rsa-cert.pem -inkey rsa-priv.pem
```

```
>openssl cms -sign -nodetach -outform DER -in msg.txt -text -out out.msg
 -signer mldsa-cert.pem -inkey mldsa-priv.pem
80DB4484BE7E0000:error:17000080:CMS routines:CMS_add1_signer:no default
 digest:crypto/cms/cms_sd.c:405:pkey nid=-1
```

```
>openssl cms -sign -nodetach -outform DER -in msg.txt -text -out out.msg
 -signer mldsa-cert.pem -inkey mldsa-priv.pem -md SHA512/SHAKE256
```

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# Hybrid certificates

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# Hybrid/Chimera Certificate Testing

Issue Hybrid Certificate (X.509 altPublicKey/Sig) to popular products.
TLS cert chains with RSA/EC+ML-DSA (Root CA -> Server/Client cert)

Servers (work - ignores ML-DSA as expected)

- WildFly 26 with JKS keystore
- Apache Httpd 2.4.55 with PEM keystore
- Enrolling for using CertBot (ACME) provided with a hybrid CSR

Clients (work - ignores ML-DSA as expected)

- Firefox 120 as TLS client with a hybrid client cert
- B-L4S5I-IOT01A (Cortex-M4) with an ISM43362 WiFi module, running mBedOS 6.17.0 and mBedTLS with hybrid client cert for mTLS

Only one private key used on client!

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# Chimera TLS (authentication) Testing

Bouncy Castle, WolfSSL and Wells Fargo on X9.146 CKS (PQC Conference January 2025)

Working PoC

- Server have dual keys and hybrid (or dual) certificate(s)
- If client signals support for ML-DSA for authentication it is used
- If client does not support ML-DSA, RSA or EC is used for authentication
- Successful PoC, standard is not finished

Complex migrations

# Composite Certificate Testing

Composite ML-DSA for use in X.509 Public Key Infrastructure

Bouncy Castle

- Draft 7, July 2025 (breaking change)
- No backwards compatibility – belts and suspenders model
- Anticipated  industry adoption for specific use cases
    - Code signing/secure boot

⤭

Full stack migrations

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# Protocols and Crypto Agility

## CMP

Plain signatures of small data

CRMF (incl ML-KEM) or PKCS#10 CSRs

## EST

TLS and plain, small signatures

PKCS#10 CSRs (ML-DSA only)

## ACME

TLS and small challenges

PKCS#10 CSRs (ML-DSA only)

## ~~SCEP~~

Signing and encryption based on CMS

Requires standards update

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# Summary

- Is there time to procrastinate? ✕ No
- Is it easy to start a PoC? ✓ Yes
- Will you find issues along the way? ✓ Yes
- Is everything production ready? ✕ No
- Can you contribute ✓ Yes
- Is it expensive to start testing ✕ No
- Hybrids and Composites ⚠ Not out of the box

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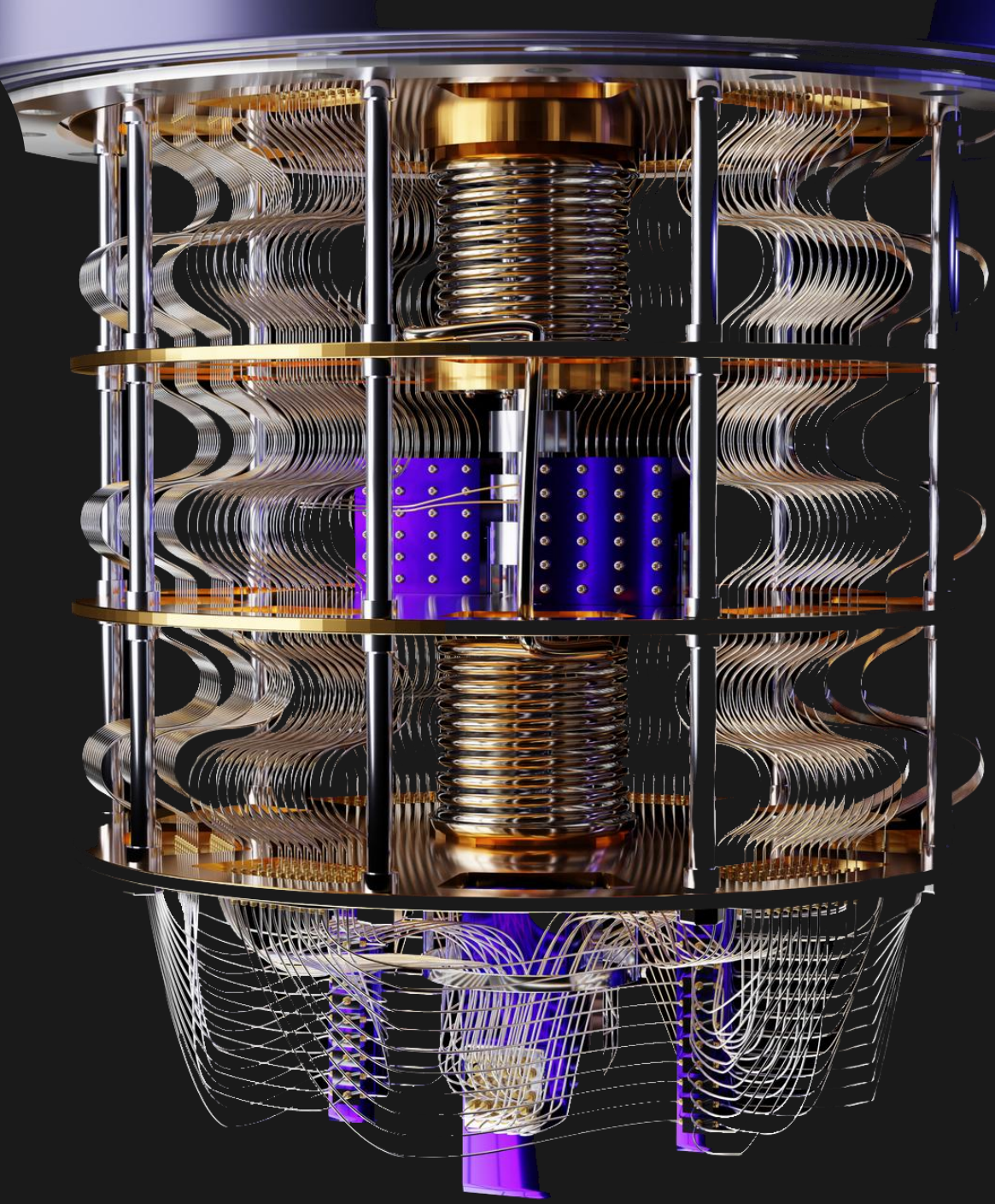
A Practical Update to

# Post-Quantum Cryptography

**Tomas Gustavsson**

Chief PKI Officer



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