Prototyping post-quantum and hybrid key exchange and authentication in TLS and SSH

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https://eprint.iacr.org/2019/858

https://github.com/awslabs/s2n

https://github.com/open-quantum-safe/

Overview

- Design considerations for hybrid modes of key exchange in general
- Case studies: designs and experimental outcomes
  - Key exchange:
    - TLS 1.2 in OpenSSL 1.0.2 and Amazon s2n
    - TLS 1.3 in OpenSSL 1.1.1
    - SSH v2 in OpenSSH 7.9
  - Authentication:
    - TLS 1.3 in OpenSSL 1.1.1
    - SSH v2 in OpenSSH 7.9

Design considerations for hybrid modes of key exchange

Douglas Stebila, Scott Fluhrer, Shay Gueron. Design issues for hybrid key exchange in TLS 1.3. Internet-Draft. Internet Engineering Task Force, July 2019. https://tools.ietf.org/html/draft-stebila-tls-hybrid-design-01

Hybrid key exchange

- Multiple sources of interest in using multiple key exchange algorithms simultaneously as part of transition to post-quantum crypto
  - Several Internet-Drafts already:
    - TLS 1.2: Schanck, Whyte, Zhang 2016; Amazon 2019
    - TLS 1.3: Schanck, Stebila 2017; Whyte, Zhang, Fluhrer, Garcia-Morchon 2017; Kiefer, Kwiatkowski 2018; Stebila, Fluhrer, Gueron 2019
  - Experimental implementations: Google CECPQ1, CECPQ2; Open Quantum Safe; CECPQ2b; …
- Need PQ key exchange before we need PQ authentication because future quantum computers could retroactively decrypt, but not retroactively impersonate

Goals for hybridization

1. Backwards compatibility
    - Hybrid-aware client, hybrid-aware server
    - Hybrid-aware client, non-hybrid-aware server
    - Non-hybrid-aware client, hybrid-aware server
2. Low computational overhead
3. Low latency
4. No extra round trips
5. No duplicate information

Design options

- How to negotiate algorithms
- How to convey cryptographic data (public keys / ciphertexts)
- How to combine keying material

Negotiation: How many algorithms?

2

≥ 2

Negotiation: How to indicate which algorithms to use

Negotiate each algorithm individually

1. Standardize a name for each algorithm
2. Provide a data structure for conveying supported algorithms
3. Implement logic negotiating which combination

Negotiate pre-defined combinations of algorithms

1. Standardize a name for each desired combination

- Can use existing negotiation data structures and logic

Which option is preferred may depend on how many algorithms are ultimately standardized.

Conveying cryptographic data (public keys / ciphertexts)

1) Separate public keys

- For each supported algorithm, send each public key / ciphertext in its own parseable data structure

2) Concatenate public keys

- For each supported combination, concatenate its public keys / ciphertext into an opaque data structure

#1 requires protocol and implementation changes

#2 abstracts combinations into “just another single algorithm”

But #2 can also lead to sending duplicate values

- nistp256+bike1l1
- nistp256+sikep403
- nistp256+frodo640aes
- sikep403+frodo640aes

3x nistp256,
2x sikep403,
2x frodo640aes
public keys

Combining keying material

Top requirement: needs to provide "robust" security:

- Final session key should be secure as long as at least one of the ingredient keys is unbroken
- (Most obvious techniques are fine, though with some subtleties; see Giacon et al. PKC 2018, Bindel et al. PQCrypto 2019, … .)

- XOR keys
- Concatenate keys and use directly
- Concatenate keys then apply a hash function / KDF
- Extend the protocol's "key schedule" with new stages for each key
- Insert the 2nd key into an unused spot in the protocol's key schedule

Emerging consensus?

- **Combining keying material**: concatenate keys then apply hash function / KDF

- **Number of algorithms**: 2 vs ≥ 2: no consensus
- **Negotiation**: negotiate algorithms separately versus in combination: no consensus
  - All(?) implementations to date have negotiated pre-defined combinations
- **Conveying public keys**: separately versus concatenated: no consensus
  - All(?) implementations to date have used concatenation

Key exchange case studies

Case study 1: TLS 1.2 in Amazon s2n

- Multi-level negotiation following TLS 1.2 design style:
  - Top-level ciphersuite with algorithm family: e.g. `TLS_ECDHE_SIKE_ECDSA_WITH_AES_256_GCM_SHA384`
  - Extensions used to negotiate parameterization within family:
    - 1 extension for which ECDH elliptic curve: nistp256, curve25519, …
    - 1 extension for which PQ parameterization: sikep403, sikep504, …
- Session key: concatenate session keys and apply KDF with public key/ciphertext as KDF label
- Experimental results: successfully implemented using nistp256+{bike1l1, sikep503}

Implementation base for rest of case studies

- Implementations from Open Quantum Safe project's liboqs library
  - Open-source C library collecting implementations of many round 2 KEMs and signature schemes – directly from contributors, from NIST submission packages, or via PQClean
  - https://github.com/open-quantum-safe
- Algorithms tested:
  - KEMs: 9 of 17 (BIKE round 1, FrodoKEM, Kyber, LEDAcrypt, NewHope, NTRU, NTS (1 variant), Saber, SIKE)
  - Signature schemes: 6 of 9 (Dilithium, MQDSS, Picnic, qTesla (round 1), Rainbow, SPHINCS+)

Case study 2: TLS 1.2 in OpenSSL 1.0.2
Case study 3: TLS 1.3 in OpenSSL 1.1.1
Case study 4: SSH v2 in OpenSSH 7.9

- Negotiate pairs of algorithms in pre-defined combinations
- Session key: concatenate session keys and use directly in key schedule

- Easy implementation, no change to negotiation logic

1st circle: PQ only
2nd circle: hybrid ECDH

● = success

◓ = fixable by changing implementation parameter

○ = would violate spec or otherwise unresolved error

† = algorithm on testing branch

	s2n (TLS 1.2)	OpenSSL 1.0.2 (TLS 1.2)	OpenSSL 1.1.1 (TLS 1.3)	OpenSSH
BIKE1-L1 (round 1)	–●	●●	●●	●●
BIKE1-L3 (round 1)	– –	●●	●●	●●
BIKE1-L5 (round 1)	– –	●●	●●	●●
BIKE2-L1 (round 1)	– –	●●	●●	●●
BIKE2-L3 (round 1)	– –	●●	●●	●●
BIKE2-L5 (round 1)	– –	●●	●●	●●
BIKE3-L1 (round 1)	– –	●●	●●	●●
BIKE3-L3 (round 1)	– –	●●	●●	●●
BIKE3-L5 (round 1)	– –	●●	●●	●●
FrodoKEM-640-AES	– –	●●	●●	●●
FrodoKEM-640-SHAKE	– –	●●	●●	●●
FrodoKEM-976-AES	– –	●●	●●	●●
FrodoKEM-976-SHAKE	– –	●●	●●	●●
FrodoKEM-1344-AES	– –	◓◓	◓◓	●●
FrodoKEM-1344-SHAKE	– –	◓◓	◓◓	●●
Kyber512	– –	●●	●●	●●
Kyber768	– –	●●	●●	●●
Kyber1024	– –	●●	●●	●●
LEDAcrypt-KEM-LT-12†	– –	●●	●●	●●
LEDAcrypt-KEM-LT-32†	– –	●●	●●	●●
LEDAcrypt-KEM-LT-52†	– –	●●	●●	●●
NewHope-512-CCA	– –	●●	●●	●●
NewHope-1024-CCA	– –	●●	●●	●●
NTRU-HPS-2048-509	– –	●●	●●	●●
NTRU-HPS-2048-677	– –	●●	●●	●●
NTRU-HPS-4096-821	– –	●●	●●	●●
NTRU-HRSS-701	– –	●●	●●	●●
NTS-KEM(12,64)†	– –	○○	○○	○○
LightSaber-KEM	– –	●●	●●	●●
Saber-KEM	– –	●●	●●	●●
FireSaber-KEM	– –	●●	●●	●●
SIKEp503 (round 1)	–●	– –	– –	– –
SIKEp434	– –	●●	●●	●●
SIKEp503	– –	●●	●●	●●
SIKEp610	– –	●●	●●	●●
SIKEp751	– –	●●	●●	●●

FrodoKEM 976, 1344

- OpenSSL 1.0.2 / TLS 1.2: too large for a pre-programmed buffer size, but easily fixed by increasing one buffer size
- OpenSSL 1.1.1 / TLS 1.3: same

NTS-KEM

- OpenSSL 1.0.2 / TLS 1.2: theoretically within spec's limitation of 2^{24} bytes, but buffer sizes that large caused failures we couldn't track down
- OpenSSL 1.1.1 / TLS 1.3: too large for spec (2^{16}-1 bytes)
- OpenSSH: theoretically within spec but not within RFC's "SHOULD", but couldn't resolve bugs

Authentication case studies

1st circle: PQ only
2nd circle: hybrid RSA

● = success

◓ = fixable by changing implementation parameter

◯ = would violate spec or otherwise unresolved error

† = algorithm on testing branch

	OpenSSL 1.1.1 (TLS 1.3)
Dilithium-2	● ●
Dilithium-3	● ●
Dilithium-4	● ●
MQDSS-31-48	◓ ◓
MQDSS-31-64	◓ ◓
Picnic-L1-FS	◓ ◓
Picnic-L1-UR	◓ ◓
Picnic-L3-FS	◯ ◯
Picnic-L3-UR	◯ ◯
Picnic-L5-FS	◯ ◯
Picnic-L5-UR	◯ ◯
Picnic2-L1-FS	● ●
Picnic2-L3-FS	◓ ◓
Picnic2-L5-FS	◓ ◓
qTesla-I (round 1)	● ●
qTesla-III-size (round 1)	● ●
qTesla-III-speed (round 1)	● ●
Rainbow-Ia-Classic†	◓ ◓
Rainbow-Ia-Cyclic†	● ●
Rainbow-Ia-Cyclic-Compressed†	● ●
Rainbow-IIIc-Classic†	◓ ◓
Rainbow-IIIc-Cyclic†	◓ ◓
Rainbow-IIIc-Cyclic-Compressed†	◓ ◓
Rainbow-Vc-Classic†	◓ ◓
Rainbow-Vc-Cyclic†	◓ ◓
Rainbow-Vc-Cyclic-Compressed†	◓ ◓
SPHINCS+-{Haraka,SHA256,SHAKE256}-128f-{robust,simple}	◓ ◓
SPHINCS+-{Haraka,SHA256,SHAKE256}-128s-{robust,simple}	● ●
SPHINCS+-{Haraka,SHA256,SHAKE256}-192f-{robust,simple}	◓ ◓
SPHINCS+-{Haraka,SHA256,SHAKE256}-192s-{robust,simple}	◓ ◓
SPHINCS+-{Haraka,SHA256,SHAKE256}-256f-{robust,simple}	◓ ◓
SPHINCS+-{Haraka,SHA256,SHAKE256}-256s-{robust,simple}	◓ ◓

TLS 1.3:
- Max certificate size: $2^{24}-1$
- Max signature size: $2^{16}-1$

OpenSSL 1.1.1:
- Max certificate size: 102,400 bytes, but runtime enlargeable
- Max signature size: 2^{14}

1st circle: PQ only
2nd circle: hybrid RSA

● = success

◓ = fixable by changing implementation parameter

○ = would violate spec or otherwise unresolved error

† = algorithm on testing branch

	OpenSSL 1.1.1 (TLS 1.3)	OpenSSH
Dilithium-2	● ●	● ●
Dilithium-3	● ●	● ●
Dilithium-4	● ●	● ●
MQDSS-31-48	◓ ◓	● ●
MQDSS-31-64	◓ ◓	● ●
Picnic-L1-FS	◓ ◓	● ●
Picnic-L1-UR	◓ ◓	● ●
Picnic-L3-FS	○ ○	● ●
Picnic-L3-UR	○ ○	● ●
Picnic-L5-FS	○ ○	● ●
Picnic-L5-UR	○ ○	● ●
Picnic2-L1-FS	● ●	● ●
Picnic2-L3-FS	◓ ◓	● ●
Picnic2-L5-FS	◓ ◓	● ●
qTesla-I (round 1)	● ●	● ●
qTesla-III-size (round 1)	● ●	● ●
qTesla-III-speed (round 1)	● ●	● ●
Rainbow-Ia-Classic†	◓ ◓	◓ ◓
Rainbow-Ia-Cyclic†	● ●	● ●
Rainbow-Ia-Cyclic-Compressed†	● ●	● ●
Rainbow-IIIc-Classic†	◓ ◓	○ ○
Rainbow-IIIc-Cyclic†	◓ ◓	○ ○
Rainbow-IIIc-Cyclic-Compressed†	◓ ◓	○ ○
Rainbow-Vc-Classic†	◓ ◓	○ ○
Rainbow-Vc-Cyclic†	◓ ◓	○ ○
Rainbow-Vc-Cyclic-Compressed†	◓ ◓	○ ○
SPHINCS+-{Haraka,SHA256,SHAKE256}-128f-{robust,simple}	◓ ◓	● ●
SPHINCS+-{Haraka,SHA256,SHAKE256}-128s-{robust,simple}	● ●	● ●
SPHINCS+-{Haraka,SHA256,SHAKE256}-192f-{robust,simple}	◓ ◓	● ●
SPHINCS+-{Haraka,SHA256,SHAKE256}-192s-{robust,simple}	◓ ◓	● ●
SPHINCS+-{Haraka,SHA256,SHAKE256}-256f-{robust,simple}	◓ ◓	● ●
SPHINCS+-{Haraka,SHA256,SHAKE256}-256s-{robust,simple}	◓ ◓	● ●

OpenSSH maximum packet size: 2^{18}

Summary

Summary

- Several design choices for hybrid key exchange in network protocols on negotiation and transmitting public keys, no consensus
- Protocols have size constraints which prevent some schemes from being used
- Implementations may have additional size constraints which affect some schemes, which can be bypassed with varying degrees of success

Extensions and open questions

Remaining Round 2 candidates

- Welcome help in getting code into our framework – either directly into liboqs or via PQClean

Constraints in other parts of the protocol ecosystem

- Other client/server implementations
- Middle boxes

Performance

- Latency and throughput in lab conditions
- Latency in realistic network conditions à la [Lan18]

Use in applications

- Tested our OpenSSL experiment with Apache, nginx, links, OpenVPN, with reasonable success
- More work to do:
  S/MIME, more TLS clients, …

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