# Transitioning the TLS protocol to post-quantum cryptography

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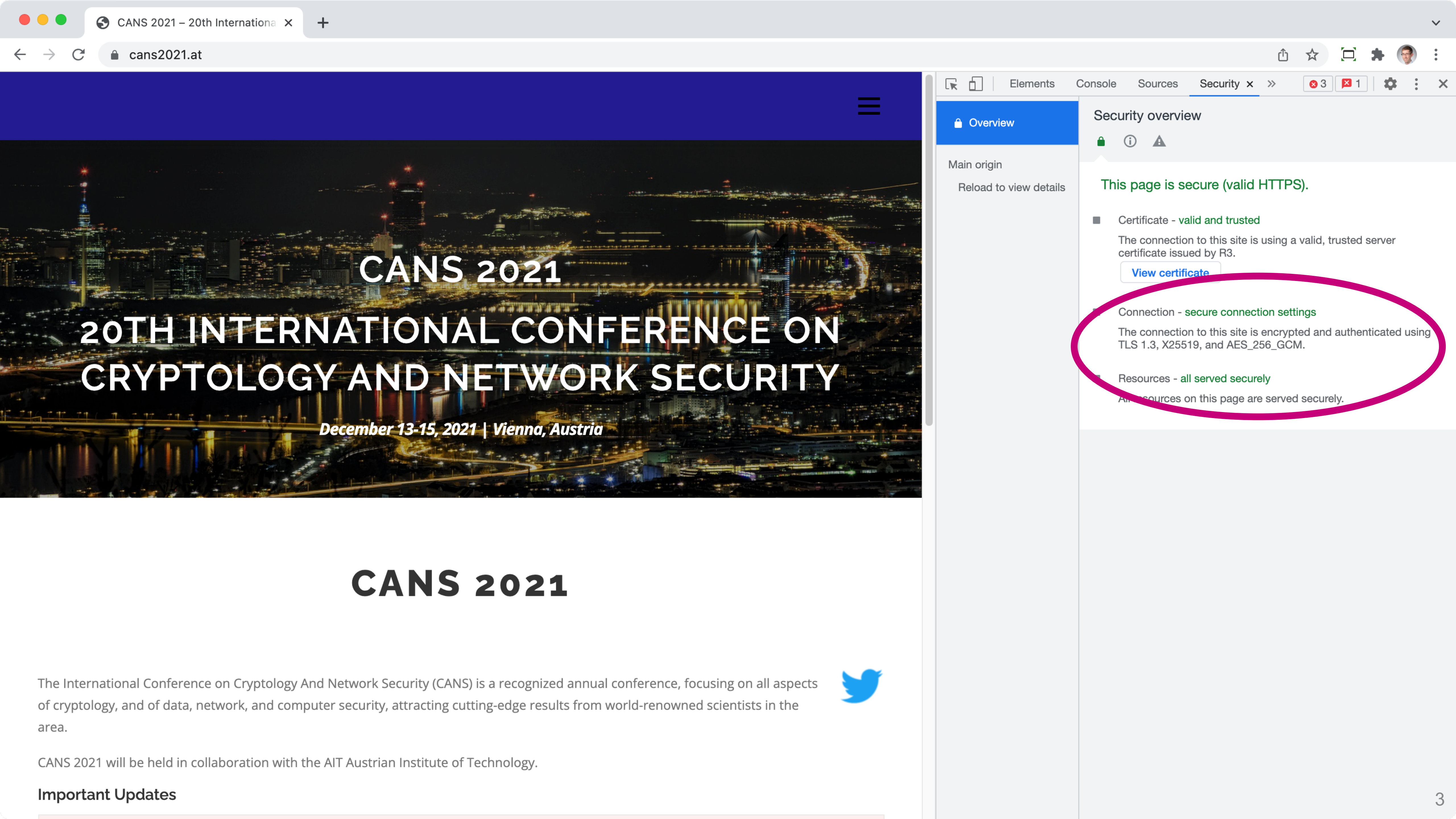
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Elements
Console
Sources
Security
Overview
Main origin
Reload to view details
Security overview
This page is secure (valid HTTPS).
Certificate - valid and trusted
The connection to this site is using a valid, trusted server certificate issued by R3.
View certificate
Connection - secure connection settings
The connection to this site is encrypted and authenticated using TLS 1.3, X25519, and AES_256_GCM.
Resources - all served securely
All resources on this page are served securely.
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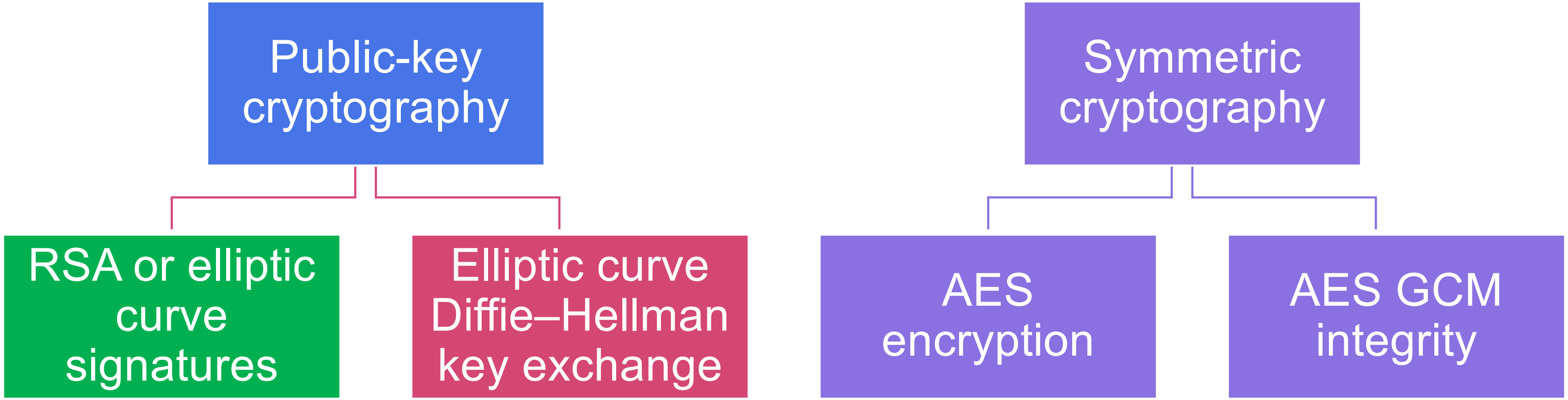
CANS 2021
The International Conference on Cryptology And Network Security (CANS) is a recognized annual conference, focusing on all aspects of cryptology, and of data, network, and computer security, attracting cutting-edge results from world-renowned scientists in the area.
CANS 2021 will be held in collaboration with the AIT Austrian Institute of Technology.
Important Updates

# Cryptographic building blocks

Connection - secure connection settings

The connection to this site is encrypted and authenticated using TLS 1.3, X25519, and AES_256_GCM.



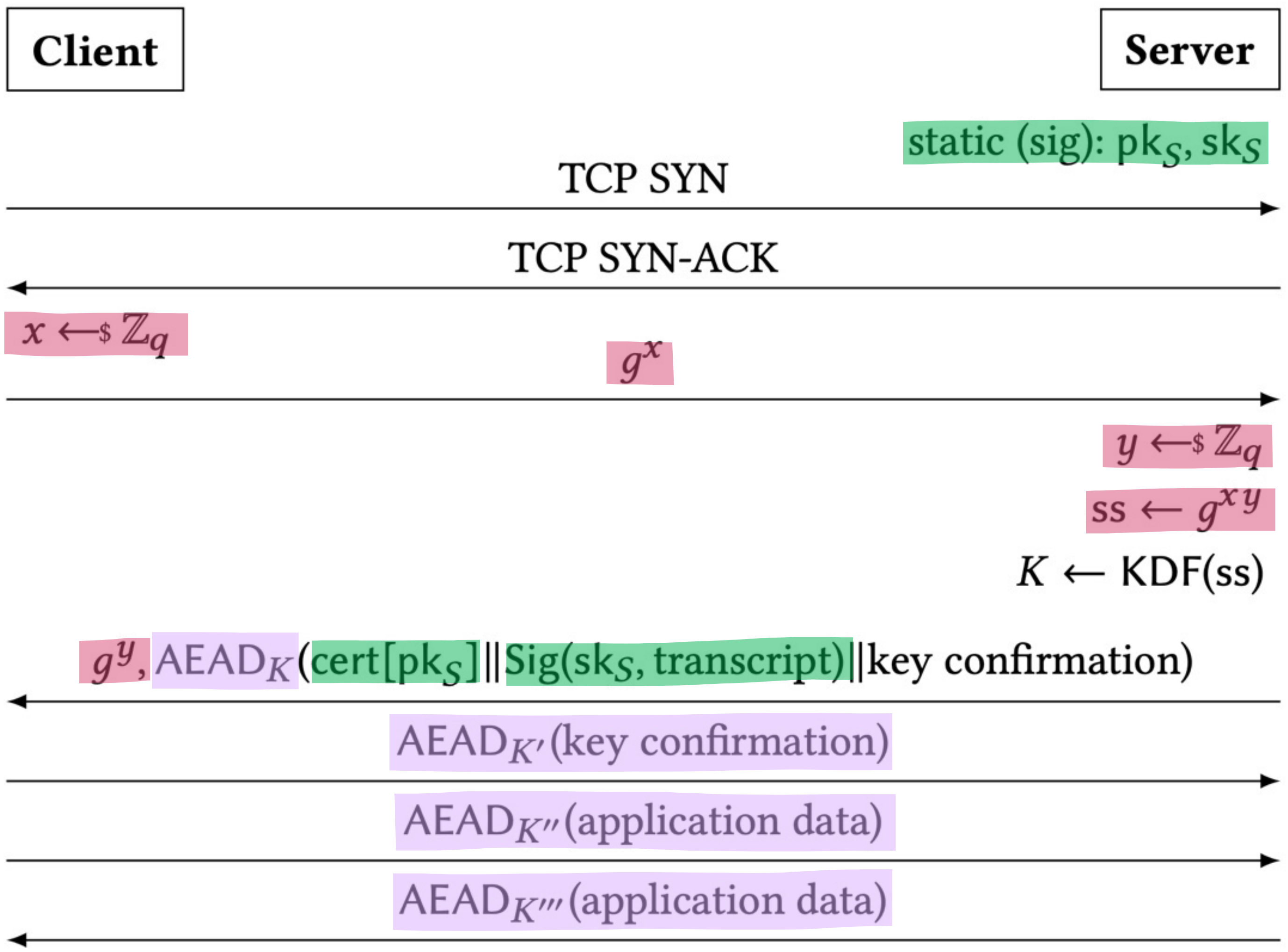
# TLS 1.3 handshake

Diffie-Hellman key exchange

Digital signature

Signed Diffie–Hellman

Authenticated encryption



# Cryptographic building blocks

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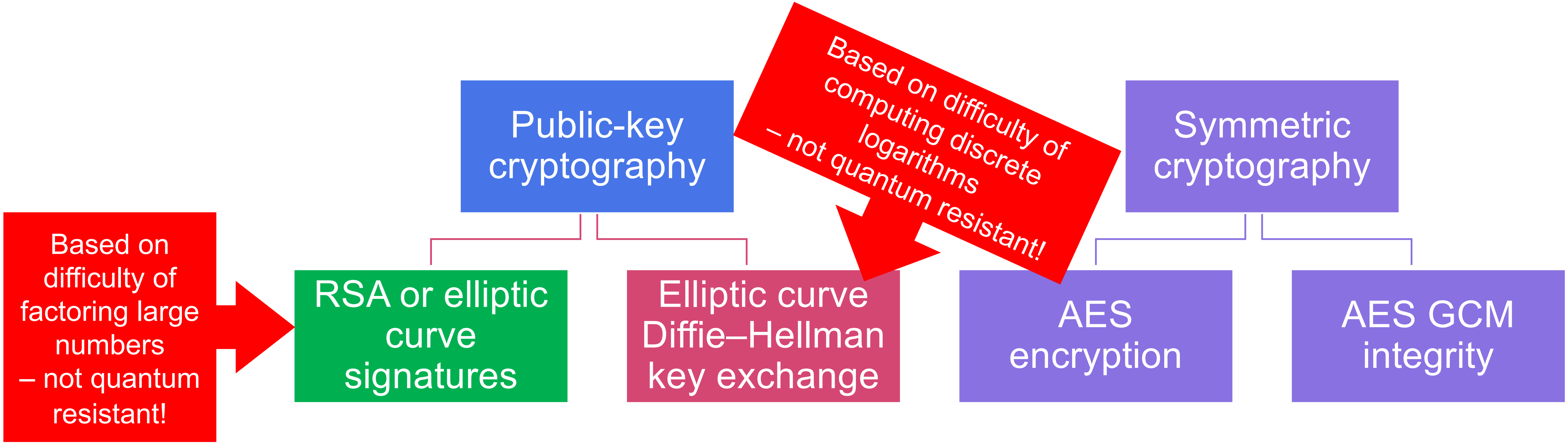


# Post-quantum cryptography

a.k.a. quantum-resistant algorithms

**Cryptography believed to be resistant to attacks by quantum computers**

Uses only classical (non-quantum) operations to implement

Hash-based & symmetric

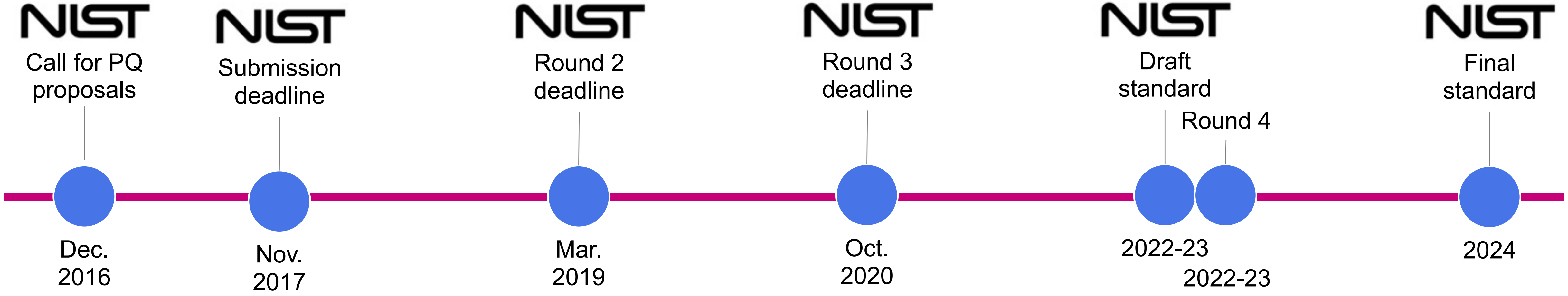
Multivariate quadratic

Code-based

Lattice-based

Elliptic curve isogenies

# NIST Post-quantum Crypto Project timeline




Round 1:
69 schemes
1/3 signatures
2/3 PKE

Round 2:
26 schemes
9 signatures
17 PKE

Round 3:
Finalists:
- 3 signatures
- 4 PKE

Alternates:
- 3 signatures
- 5 PKE

http://www.nist.gov/pqcrypto

# NIST Round 3

## Finalists

**Key encapsulation mechanisms**

- Code-based: Classic McEliece
- Lattice-based: Kyber, NTRU, Saber
  - At most one of these 3 will be standardized

**Signatures**

- Lattice-based: Dilithium, Falcon
  - At most one of these 2 will be standardized
- Multivariate: Rainbow

## Alternate candidates

**Key encapsulation mechanisms**

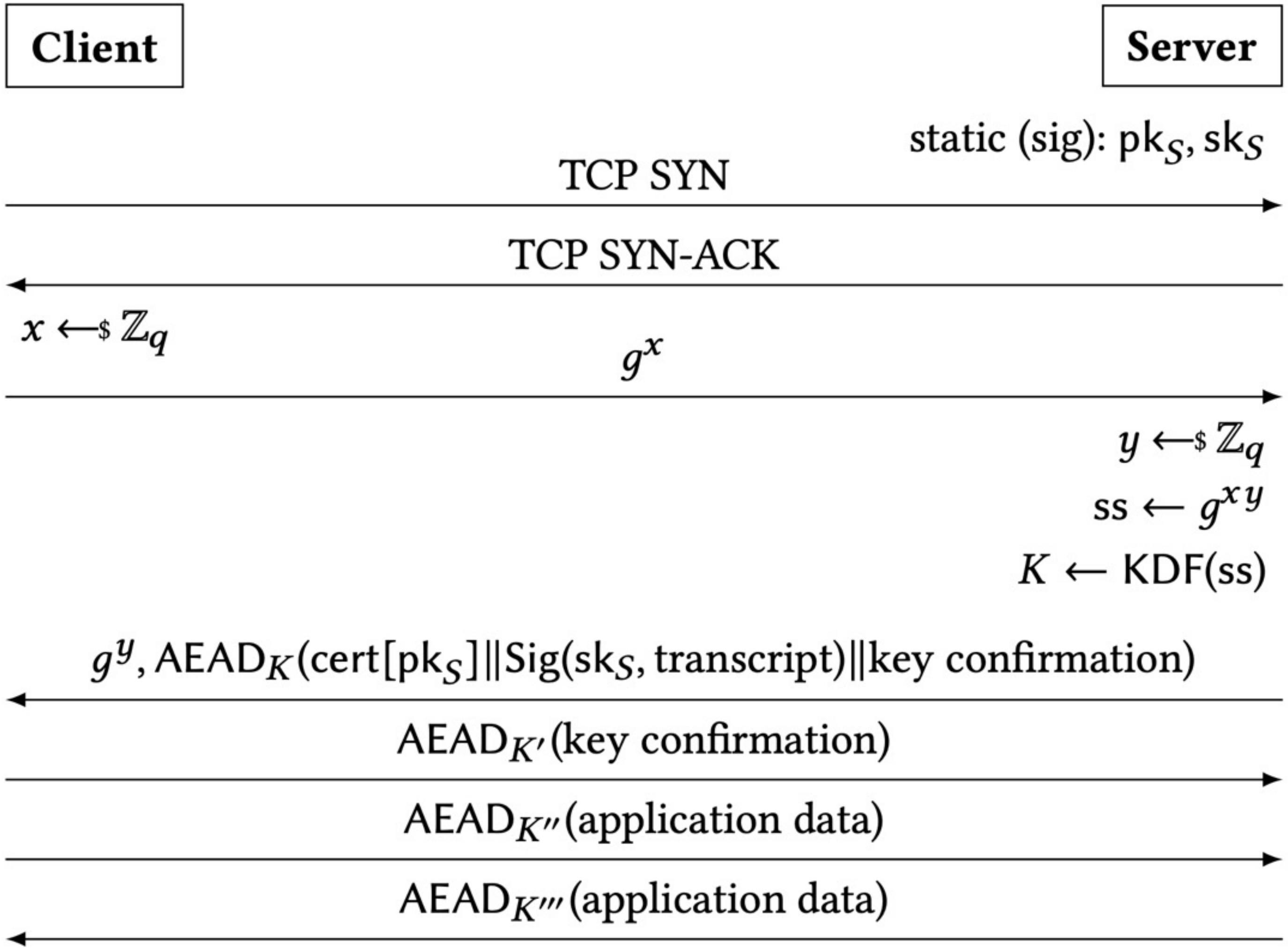
- Code-based: BIKE, HQC
- Lattice-based: FrodoKEM, NTRU Prime
- Isogeny-based: SIKE

**Signatures**

- Symmetric-based: Picnic, SPHINCS+
- Multivariate: GeMSS

# TLS 1.3 handshake

Signed Diffie–Hellman



# TLS 1.3 handshake

~~Signed Diffie–Hellman~~

Post-Quantum!!!

**Client** **Server**

PQ

static (sig): $pk_S, sk_S$

TCP SYN $\longrightarrow$

$\longleftarrow$ TCP SYN-ACK

$\cancel{x \leftarrow_{\$} \mathbb{Z}_q}$

$(pk, sk) \leftarrow$ KEM. KeyGen()

$\cancel{g^x}$ pk $\longrightarrow$

$(ct, ss) \leftarrow$ KEM. Encaps(pk)

$\cancel{y \leftarrow_{\$} \mathbb{Z}_q}$

$\cancel{ss \leftarrow g^{xy}}$

$K \leftarrow \mathrm{KDF}(ss)$

ct PQ

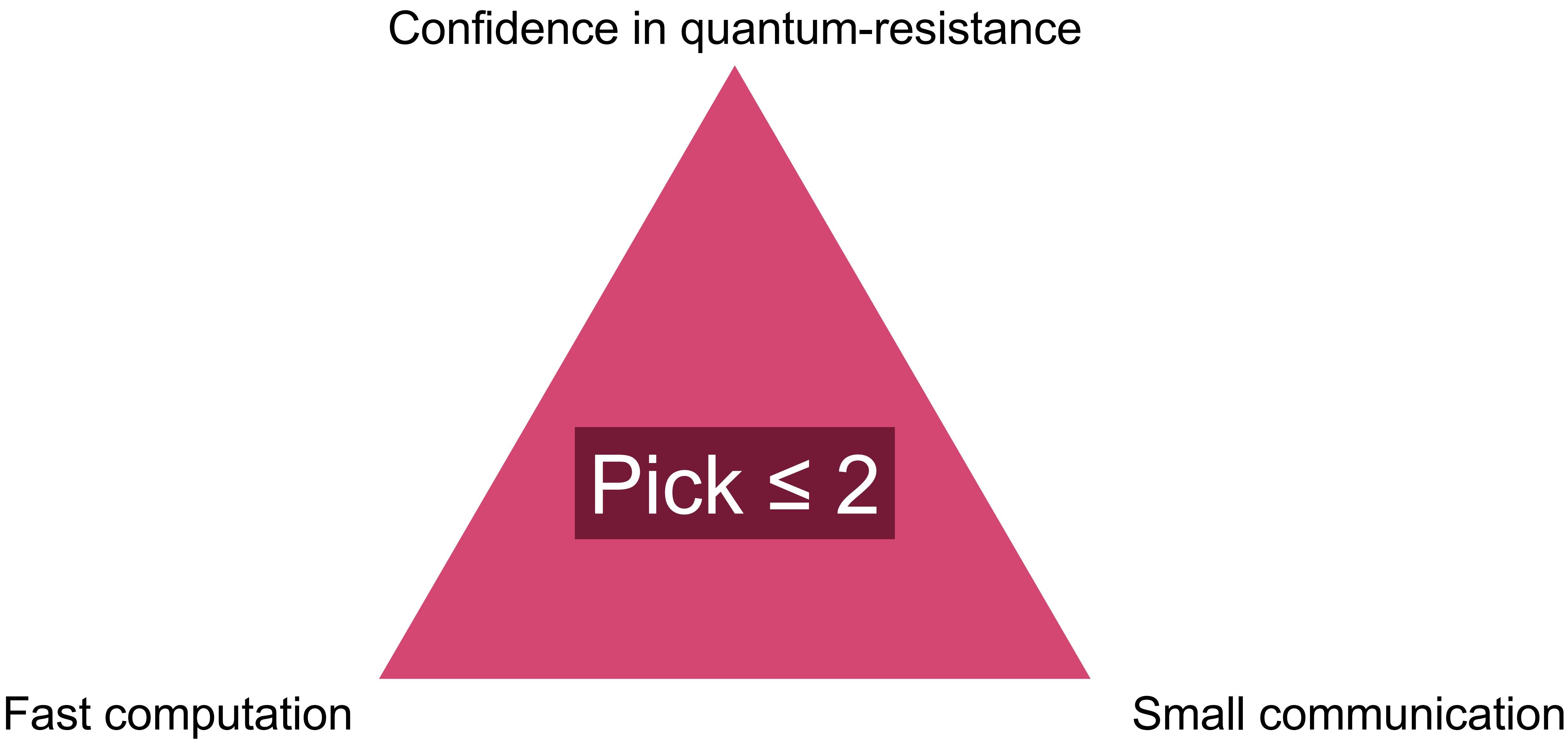
$\longleftarrow$ $\cancel{g^y}$, $\mathrm{AEAD}_K(\mathrm{cert}[pk_S] \| \mathrm{Sig}(sk_S, \mathrm{transcript}) \| \text{key confirmation})$

Decaps

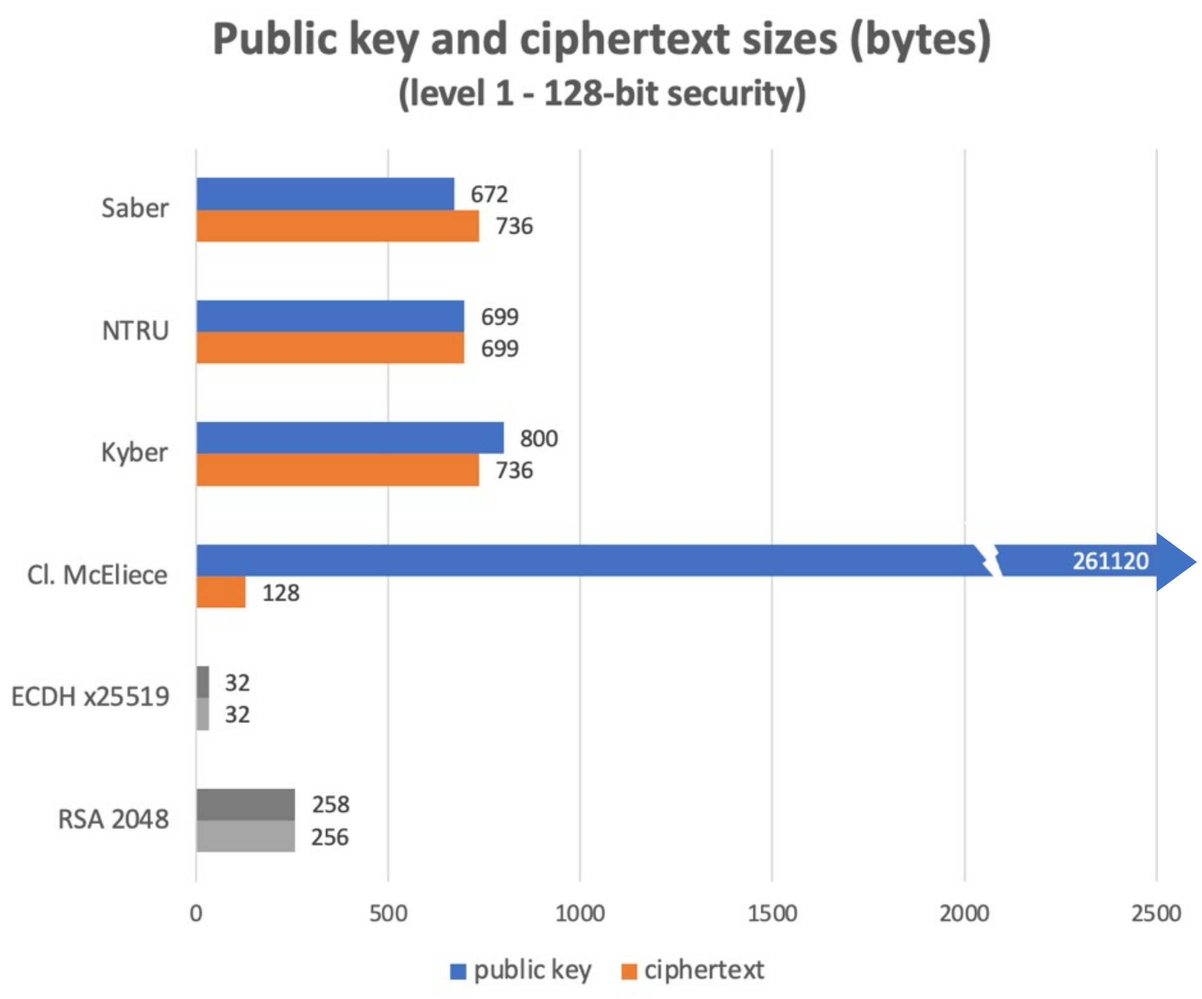
$\mathrm{AEAD}_{K'}(\text{key confirmation})$ $\longrightarrow$

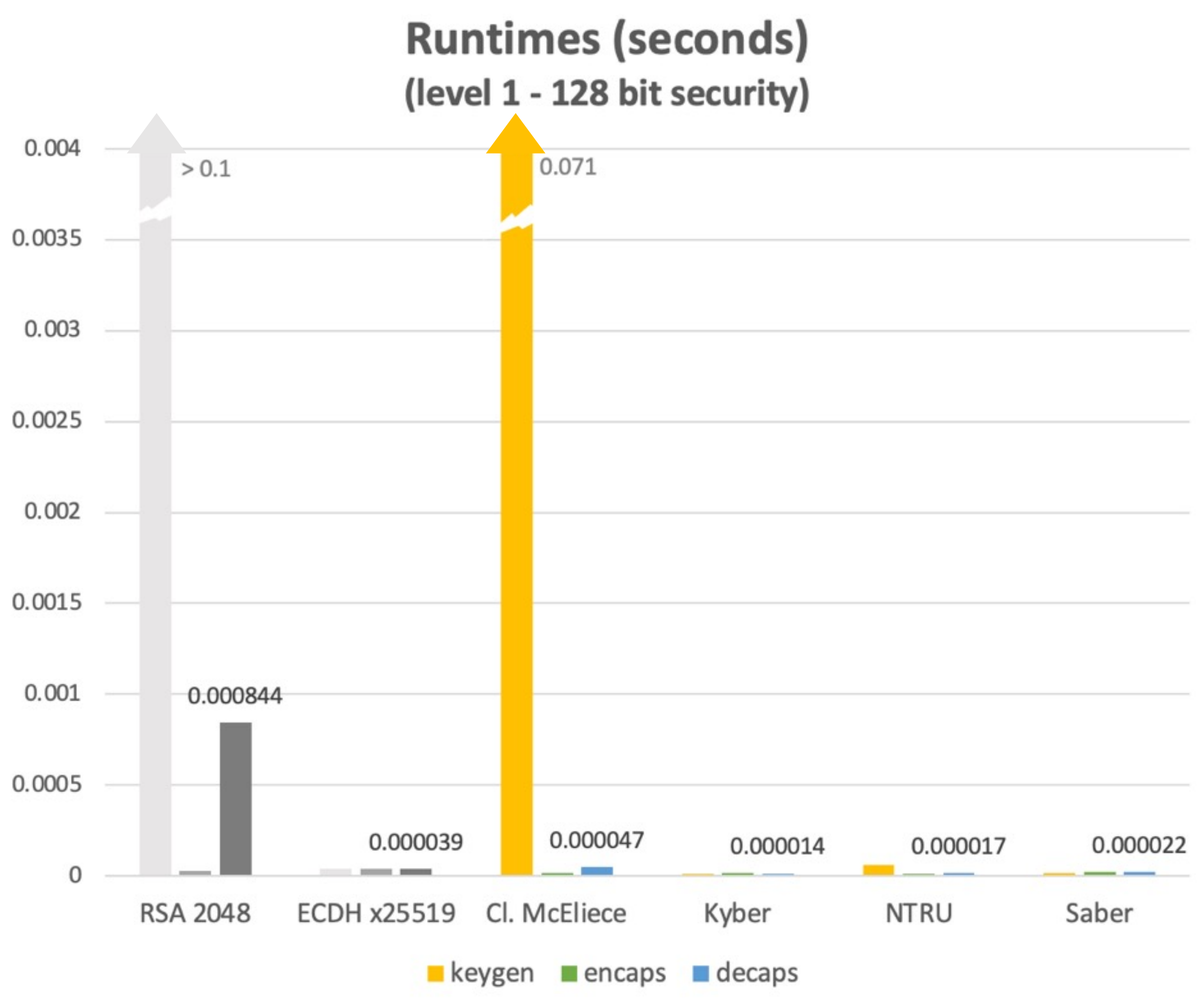
$\mathrm{AEAD}_{K''}(\text{application data})$ $\longrightarrow$

$\longleftarrow$ $\mathrm{AEAD}_{K'''}(\text{application data})$


Confidence in quantum-resistance
Pick ≤ 2
Fast computation
Small communication

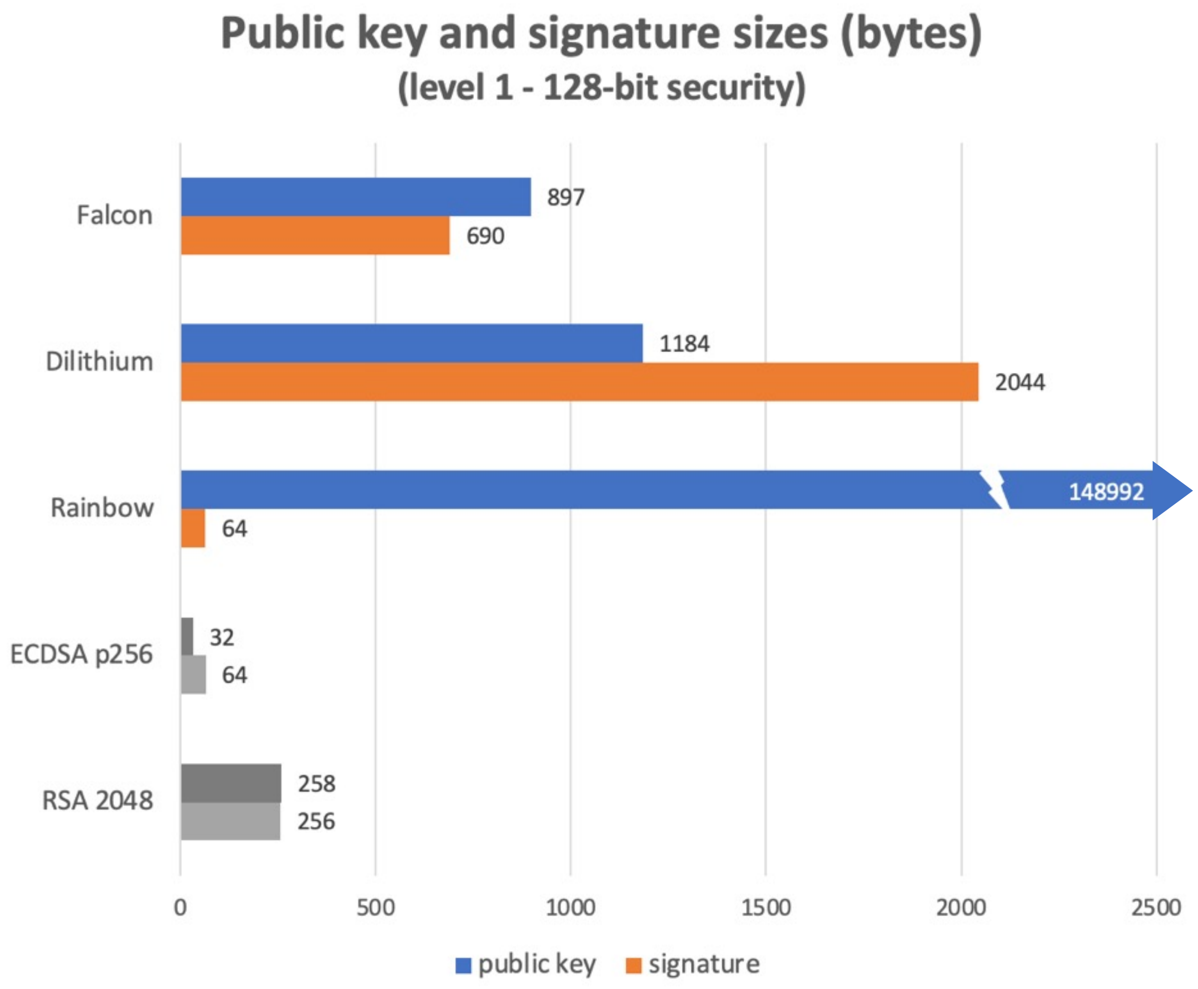
# NIST Round 3 KEM Finalists

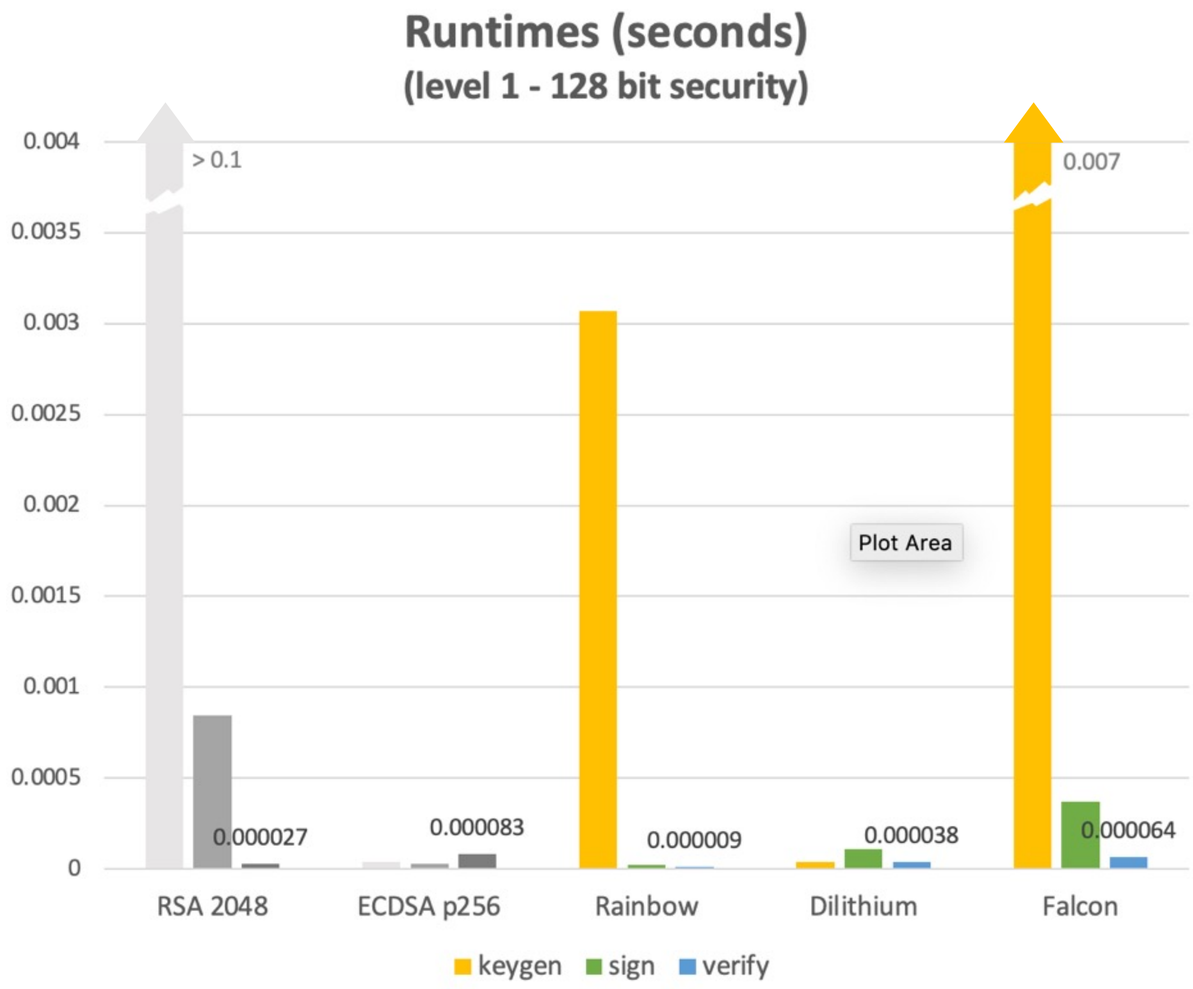



Based on Round 2 submission documents; AVX2 runtimes normalized

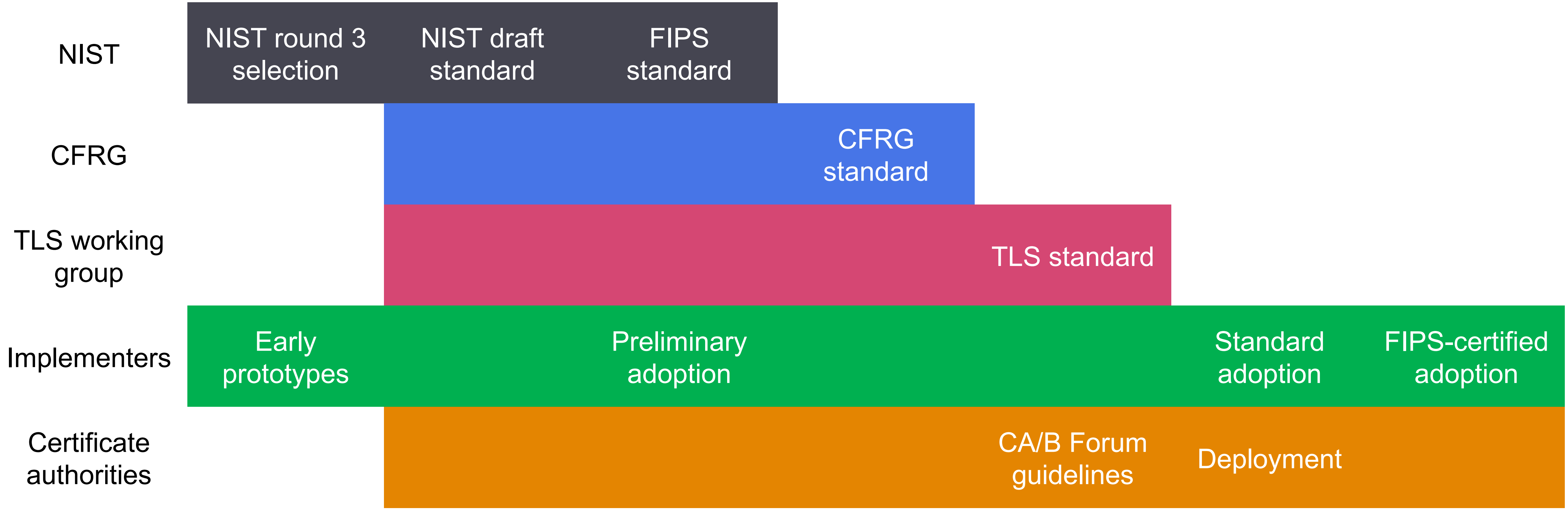
# NIST Round 3 Signature Finalists




Based on Round 2 submission documents; AVX2 runtimes normalized

# Paths to standardization and adoption



# What is “post-quantum TLS”?

## Post-quantum key exchange

- Easiest to implement
- Easy backwards compatibility
- Needed soonest: harvest now & decrypt later with quantum computer

## Classical+PQ key exchange

- Easy to implement
- Possibly in demand during pre-FIPS-certification period

## Post-quantum signatures

- Requires coordination with certificate authorities
- Less urgently: can’t retroactively break channel authentication

## Classical+PQ signatures

- May not make sense in the context of a negotiated protocol like TLS

## Alternative protocol designs

- Harder to implement; may require state machine or architecture changes

# Outline

Classical + PQ key exchange

Alternative protocol designs (KEMTLS)

# OPEN QUANTUM SAFE

*software for prototyping*
*quantum-resistant cryptography*

# Classical + PQ key exchange

Douglas Stebila, Scott Fluhrer, Shay Gueron

https://datatracker.ietf.org/doc/html/draft-ietf-tls-hybrid-design-03

# Why use two (or more) algorithms?

1. Reduce risk from break of one algorithm

2. Ease transition with improved backwards compatibility

3. Standards compliance during transition

# Why use two (or more) algorithms?

## 1. Reduce risk from break of one algorithm

- Enable early adopters to get post-quantum security without abandoning security of existing algorithms
- Retain security as long as at least one algorithm is not broken
- Uncertainty re: long-term security of existing cryptographic assumptions
- Uncertainty re: newer cryptographic assumptions

## 2. Ease transition with improved backwards compatibility

## 3. Standards compliance during transition

# Why use two (or more) algorithms?

1. Reduce risk from break of one algorithm

2. Ease transition with improved backwards compatibility

- Design backwards-compatible data structures with old algorithms that can be recognized by systems that haven't been upgraded, but new implementations will use new algorithms
- May not be necessary for negotiated protocols like TLS

3. Standards compliance during transition

# Why use two (or more) algorithms?

1. Reduce risk from break of one algorithm

2. Ease transition with improved backwards compatibility

3. Standards compliance during transition

- Early adopters may want to use post-quantum before standards-compliant (FIPS-)certified implementations are available
- Possible to combine (in a certified way) keying material from FIPS-certified (non-PQ) implementation with non-certified keying material

# Terminology

- “Hybrid”
- “Composite”
- “Dual algorithms”
- “Robust combiner” [HKNRR05]

[HKNRR05] Harnik, Kilian, Naor, Reingold, Rosen. Eurocrypt 2005.

# Hybrid key exchange in TLS 1.3

## Goals

Define data structures for negotiation, communication, and shared secret calculation for hybrid key exchange

## Non-goals

- Hybrid/composite certificates or digital signatures
- Selecting which post-quantum algorithms to use in TLS

# Mechanism

**Main idea**:
Each desired combination of traditional + post-quantum algorithm will be a new (opaque) key exchange “group”

- **Negotiation**: new named groups for each desired combination will need to be standardized
- **Key shares**: concatenate key shares for each constituent algorithm
- **Shared secret calculation**: concatenate shared secrets for each constituent algorithm and use as input to key schedule

# Other design options

## Negotiation

- 2 vs ≥2 algorithms
- More flexibility / granularity in algorithm selection
  - Extension for representing algorithm options and constraints

## Key shares

- Separately list key shares for each algorithm
- Use extensions for extra key shares
- => More efficient communication

## Shared secret calculation

- Apply KDF before inserting into key schedule
- XOR shares
- Insert into different parts of TLS key schedule

# Securely combining keying material

Is it okay to use concatenation?

$ss = k_1 \| k_2$

$ss = H(k_1 \| k_2)$

Note concatenation is the primary hybrid method approved by NIST.

- Assume at least one of $k_1$ or $k_2$ is indistinguishable from random.
- If H is a random oracle, then ss is indistinguishable from random.
- If $k_1$ and $k_2$ are fixed length and H is a dual PRF in either half of its input, then ss is indistinguishable from random.

https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-56Cr2.pdf#page=10

# What if Diffie–Hellman isn't the only risky primitive?

- Aviram et al.: What if hash function in TLS 1.3 isn't collision-resistant?
  - Not unreasonable question: MD5 and SHA-1 collision resistance broken

⇒ General problems in TLS 1.3 related to transcript hashing and authentication / session matching

⇒ What about hybrid shared secret calculation?

Aviram, Dowling, Komargodski, Paterson, Ronen, Yogev. Concatenating secrets may be dangerous, August 2021.
https://github.com/nimia/kdf_public

# Is it safe to use concatenation? ss = H(k1 || k2)

Aviram et al.:

If:

- H is not collision-resistant
  - (and H-collisions can be found within lifetime of TLS session)
- $k_1$ is adversary-controlled and variable length
- ephemeral keys are reused

then it possible to learn $k_2$.

- Based on attack on APOP (MD5-based challenge response protocol); similar to CRIME attack.

- Possible but significant assumptions:
  - Need long session lifetime
  - Ephemeral key reuse
- Assumption not satisfied:
  - $k_1$ is fixed-length for all standardized TLS 1.3 DH groups
- Worthwhile exercise: given existence of long-lived hard-to-upgrade implementations, how robust should our protocol designs be to algorithm failure?

Aviram, Dowling, Komargodski, Paterson, Ronen, Yogev. Concatenating secrets may be dangerous, August 2021.
[https://github.com/nimia/kdf_public](https://github.com/nimia/kdf_public)

# Composite certificates at the LAMPS working group

Led by Mike Ounsworth from Entrust Datacard
and Massimiliano Pala from CableLabs

(I’m not involved – just including here FYI)

# LAMPS working group

- "Limited Additional Mechanisms for PKIX and SMIME"
  - PKIX: Public key infrastructure a.k.a. X.509 certificates
  - SMIME: Secure email (encrypted/signed)

- LAMPS charter now includes milestones related to PQ
  - draft-ounsworth-pq-composite-keys-00
  - draft-ounsworth-pq-explicit-composite-keys-00
  - draft-ounsworth-pq-composite-sigs-05
  - draft-ounsworth-pq-composite-encryption-00

https://datatracker.ietf.org/wg/lamps/about/

# Composite OR versus Composite AND

In an asynchronous setting:

How is a credential with two public keys meant to be used?

- Must both algorithms be used? (Composite AND)
- Is either algorithm okay? (Composite OR)

# Alternative protocol designs: KEMTLS

Peter Schwabe, Douglas Stebila, Thom Wiggers
ACM CCS 2020. https://eprint.iacr.org/2020/534
ESORICS 2021. https://eprint.iacr.org/2021/779

Sofía Celi, Peter Schwabe, Douglas Stebila, Nick Sullivan, Thom Wiggers.
https://datatracker.ietf.org/doc/html/draft-celi-wiggers-tls-authkem-00

# Authenticated key exchange

- Two parties establish a shared secret over a public communication channel

# Vast literature on AKE protocols

- Many **security definitions** capturing various adversarial powers: BR, CK, eCK, …
- Different types of **authentication credentials**: public key, shared secret key, password, identity-based, …
- **Additional security goals**: weak/strong forward secrecy, key compromise impersonation resistance, post-compromise security, …
- Additional **protocol functionality**: multi-stage, ratcheting, …
- **Group** key exchange
- **Real-world protocols**: TLS, SSH, Signal, IKE, ISO, EMV, …
- …

# Explicit authentication

Alice receives assurance that she really is talking to Bob

# Implicit authentication

Alice is assured that only Bob would be able to compute the shared secret

# Explicitly authenticated key exchange: Signed Diffie–Hellman

| Alice | | Bob |
|---|---|---|
| $(pk_A, sk_A) \leftarrow \text{SIG.KeyGen}()$ | | $(pk_B, sk_B) \leftarrow \text{SIG.KeyGen}()$ |
| obtain $pk_B$ | | obtain $pk_A$ |
| $x \leftarrow_\$ \{0, \ldots, q-1\}$ | | |
| $X \leftarrow g^x$ | $\xrightarrow{\quad X \quad}$ | |
| | | $y \leftarrow_\$ \{0, \ldots, q-1\}$ |
| | | $Y \leftarrow g^y$ |
| | $\xleftarrow{\quad Y, \sigma_B \quad}$ | $\sigma_B \leftarrow \text{SIG.Sign}(sk_B, A\|B\|X\|Y)$ |
| $\sigma_A \leftarrow \text{SIG.Sign}(sk_A, A\|B\|X\|Y)$ | $\xrightarrow{\quad \sigma_A \quad}$ | |
| $k \leftarrow H(sid, Y^x)$ | | $k \leftarrow H(sid, X^y)$ |
| | $\xLeftrightarrow[\text{using authenticated encryption}]{\text{application data}}$ | |

# Implicitly authenticated key exchange: Double-DH

| Alice | | Bob | |
|---|---|---|---|
| $sk_A \leftarrow_\$ \{0, \ldots, q-1\}$ | | $sk_B \leftarrow_\$ \{0, \ldots, q-1\}$ | Static DH |
| $pk_A \leftarrow g^{sk_A}$ | | $pk_B \leftarrow g^{sk_B}$ | |
| obtain $pk_B$ | | obtain $pk_A$ | |
| $x \leftarrow_\$ \{0, \ldots, q-1\}$ | | $y \leftarrow_\$ \{0, \ldots, q-1\}$ | Ephemeral DH |
| $X \leftarrow g^x$ | $\xrightarrow{X}$ | $Y \leftarrow g^y$ | |
| | $\xleftarrow{Y}$ | | |
| $k \leftarrow H(sid, pk_B^{sk_A} \| Y^x)$ | | $k \leftarrow H(sid, pk_A^{sk_B} \| X^y)$ | |
| | application data $\Longleftrightarrow$ using authenticated encryption | | |

# Problem

post-quantum
signatures
are big

| Signature scheme | | Public key (bytes) | Signature (bytes) |
|---|---|---|---|
| RSA-2048 | Factoring | 272 | 256 |
| Elliptic curves | Elliptic curve discrete logarithm | 32 | 32 |
| **Dilithium** | **Lattice-based (MLWE/MSIS)** | **1,184** | **2,044** |
| **Falcon** | **Lattice-based (NTRU)** | **897** | **690** |
| **XMSS** | **Hash-based** | **32** | **979** |
| **Rainbow** | **Multi-variate** | **60,192** | **66** |

# Solution

use
post-quantum KEMs
for authentication

# Key encapsulation mechanisms (KEMs)

An abstraction of Diffie–Hellman key exchange

$(pk, sk) \leftarrow \mathsf{KEM.KeyGen}()$

$$\xrightarrow{\quad pk \quad}$$

$(ct, k) \leftarrow \mathsf{KEM.Encaps}(pk)$

$$\xleftarrow{\quad ct \quad}$$

$k \leftarrow \mathsf{KEM.Decaps}(sk, ct)$

| Signature scheme | | Public key (bytes) | Signature (bytes) |
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| KEM | | Public key (bytes) | Ciphertext (bytes) |
|---|---|---|---|
| RSA-2048 | Factoring | 272 | 256 |
| Elliptic curves | Elliptic curve discrete logarithm | 32 | 32 |
| **Kyber** | **Lattice-based (MLWE)** | **800** | **768** |
| **NTRU** | **Lattice-based (NTRU)** | **699** | **699** |
| **Saber** | **Lattice-based (MLWR)** | **672** | **736** |
| **SIKE** | **Isogeny-based** | **330** | **330** |
| **SIKE compressed** | **Isogeny-based** | **197** | **197** |
| **Classic McEliece** | **Code-based** | **261,120** | **128** |

# Implicitly authenticated KEX is not new

## In theory

- DH-based: SKEME, MQV, HMQV, …
- KEM-based: BCGP09, FSXY12, …

## In practice

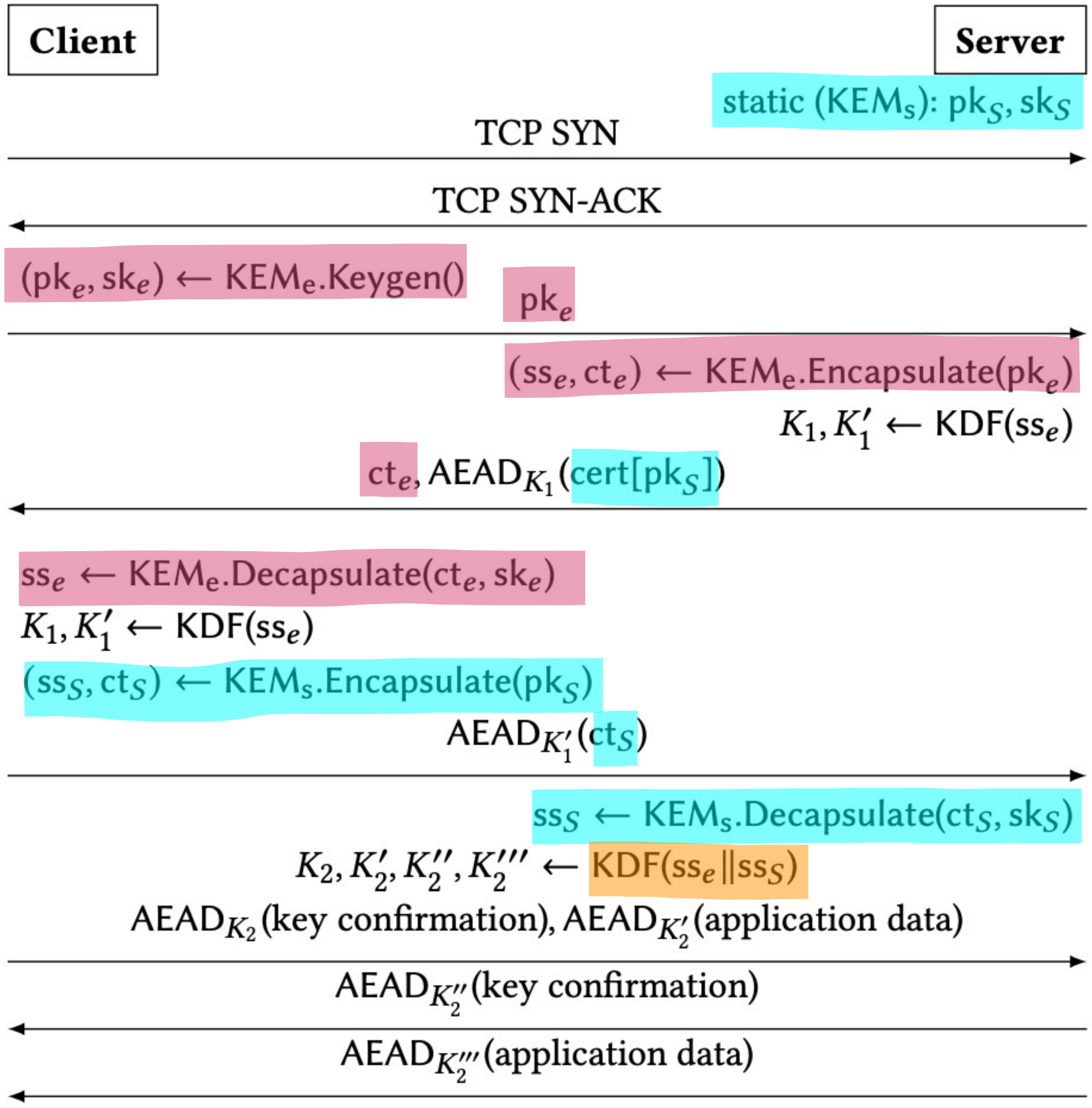
- RSA key transport in TLS ≤ 1.2
  - Lacks forward secrecy
- Signal, Noise, Wireguard
  - DH-based
  - Different protocol flows
- OPTLS
  - DH-based
  - Requires a non-interactive key exchange (NIKE)

# KEMTLS handshake

KEM for ephemeral key exchange

KEM for server-to-client authenticated key exchange

Combine shared secrets



# Algorithm choices

**KEM for ephemeral key exchange**

**KEM for authenticated key exchange**

**Signature scheme for intermediate CA**

**Signature scheme for root CA**

# Algorithm choices

**KEM for ephemeral key exchange**

- IND-CCA (or IND-1CCA)
- Want small public key + small ciphertext

**KEM for authenticated key exchange**

- IND-CCA
- Want small public key + small ciphertext

**Signature scheme for intermediate CA**

- Want small public key + small signature

**Signature scheme for root CA**

- Want small signature

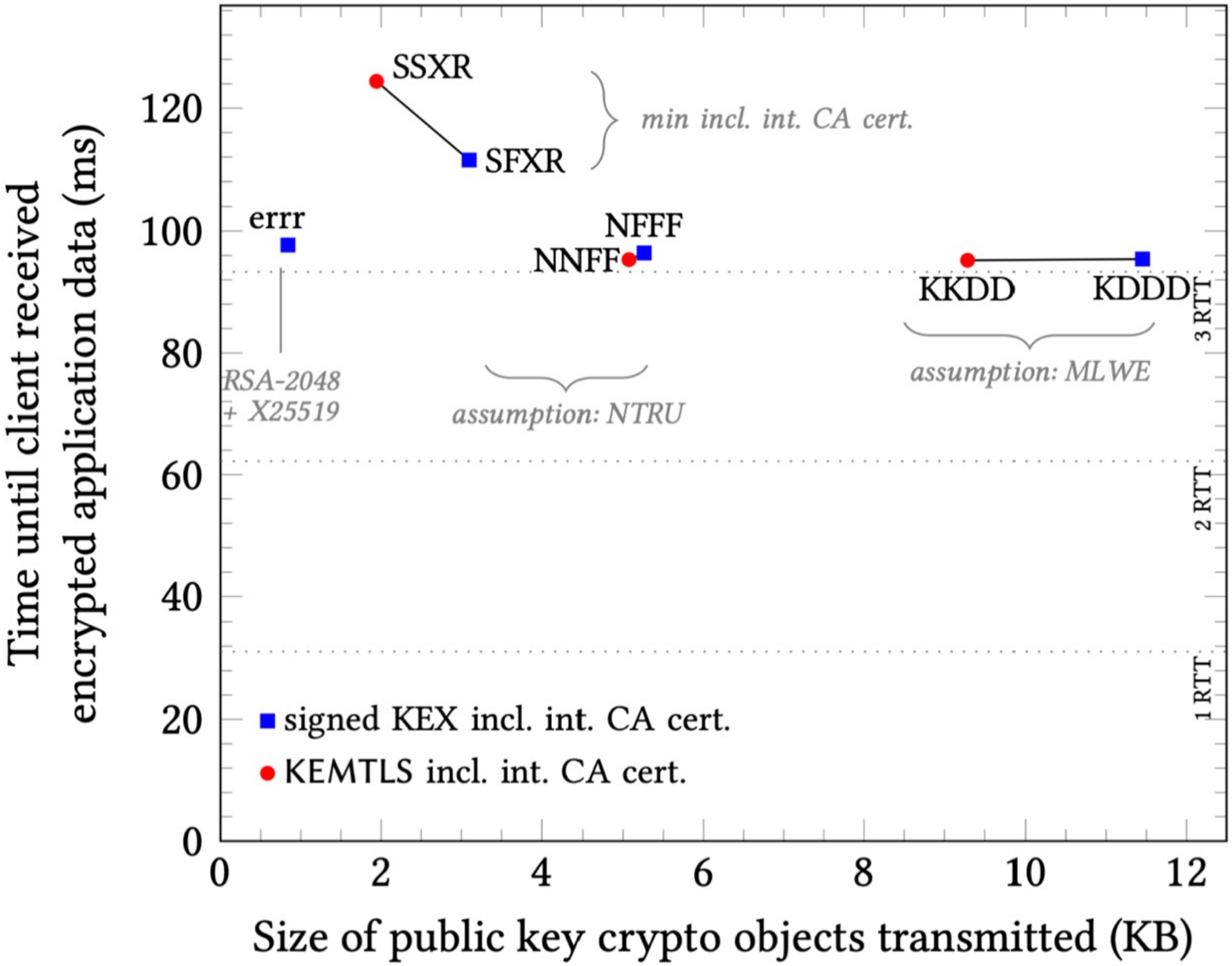
# 4 scenarios

1. Minimize size when intermediate certificate transmitted
2. Minimize size when intermediate certificate not transmitted (cached)
3. Use solely NTRU assumptions
4. Use solely module LWE/SIS assumptions

# Signed KEX versus KEMTLS

Labels ABCD:
A = ephemeral KEM
B = leaf certificate
C = intermediate CA
D = root CA

Algorithms: (all level 1)
Dilithium,
eCDH X25519,
Falcon,
Kyber,
NTRU,
Rainbow,
rSA-2048,
SIKE,
XMSS'




Rustls client/server with some AVX2 implementations. Emulated network: latency 31.1 ms, bandwidth 1000 Mbps, 0% packet loss. Average of 100000 iterations.

# Signed KEX versus KEMTLS

Labels ABCD:
A = ephemeral KEM
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Algorithms: (all level 1)
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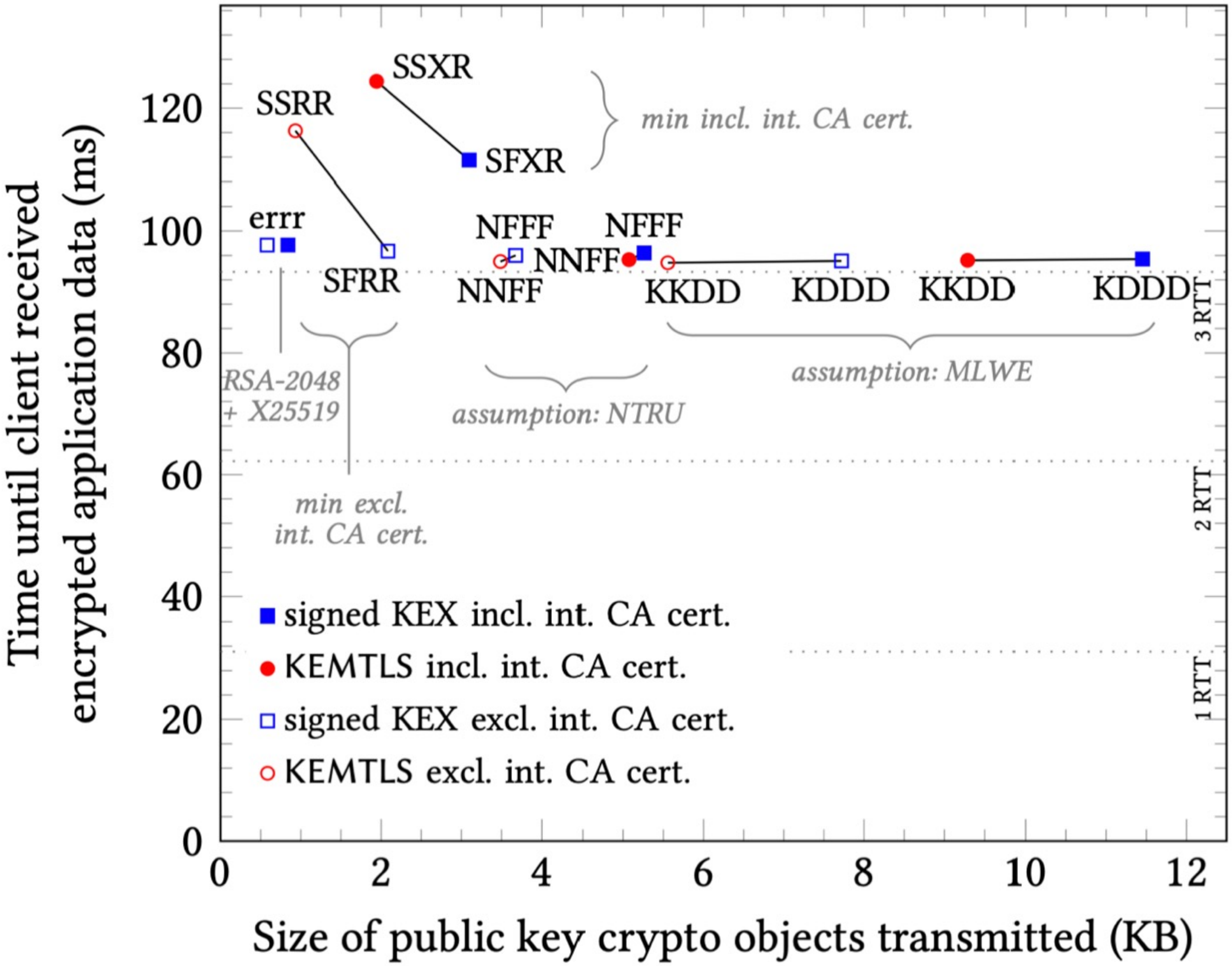



Rustls client/server with some AVX2 implementations. Emulated network: latency 31.1 ms, bandwidth 1000 Mbps, 0% packet loss. Average of 100000 iterations.

# KEMTLS benefits

- Size-optimized KEMTLS requires < ½ communication of size-optimized PQ signed-KEM
- Speed-optimized KEMTLS uses 90% fewer server CPU cycles and still reduces communication
  - NTRU KEX (27 μs) 10x faster than Falcon signing (254 μs)
- No extra round trips required until client starts sending application data
- Smaller trusted code base (no signature generation on client/server)

# Security analyses of KEMTLS

## Pen-and-paper

- In the original paper
- Proves session key security and authentication in the multi-stage key exchange model
- Using provable security paradigm

## Formal verification

Two new works underway using Tamarin prover (a symbol model checker)

1. Tamarin analog of the multi-stage key exchange model from the paper
   - https://github.com/dstebila/KEMTLS-Tamarin/
2. Modification of full-scale TLS 1.3 Tamarin model to use KEMTLS
   - https://github.com/thomwiggers/TLS13Tamarin

# Security

**Security model**: multi-stage key exchange, extending [DFGS21]

- Key indistinguishability
- Forward secrecy
- Implicit and explicit authentication

**Ingredients in security proof:**

- IND-CCA for long-term KEM
- IND-1CCA for ephemeral KEM
- Collision-resistant hash function
- Dual-PRF security of HKDF
- EUF-CMA of HMAC

[DFGS21] Dowling, Fischlin, Günther, Stebila. Journal of Cryptology, 2021. https://eprint.iacr.org/2020/1044

# Security subtleties: authentication

## Implicit authentication

- Client's first application flow can't be read by anyone other than intended server, but client doesn't know server is live at the time of sending

## Explicit authentication

- Explicit authentication once key confirmation message transmitted
- *Retroactive* explicit authentication of earlier keys

[DGK06] Di Raimondo, Gennaro, Krawczyk. ACM CCS 2006. https://eprint.iacr.org/2006/280

# Security subtleties: downgrade resilience

- Choice of cryptographic algorithms not authenticated at the time the client sends its first application flow
  - MITM can't trick client into using undesirable algorithm
  - But MITM *can* trick them into *temporarily* using suboptimal algorithm

- Formally model 3 levels of downgrade-resilience:
  1. Full downgrade resilience
  2. No downgrade resilience to unsupported algorithms
  3. No downgrade resilience

# Security subtleties: forward secrecy

Does compromise of a party's long-term key allow decryption of past sessions?

- **Weak forward secrecy 1:** adversary passive in the test stage
- **Weak forward secrecy 2:** adversary passive in the test stage or never corrupted peer's long-term key
- **Forward secrecy:** adversary passive in the test stage or didn't corrupt peer's long-term key before acceptance

# Variant: KEMTLS with client authentication

1. Client has a long-term KEM public key
2. Client transmits it encrypted under key derived from
   a) server long-term KEM key exchange
   b) ephemeral KEM key exchange

- Preserves client confidentiality
- Adds extra round trip

# Variant: Pre-distributed public keys

What if server public keys are pre-distributed?

- Cached in a browser
- Pinned in mobile apps
- Embedded in IoT devices
- Out-of-band (e.g., DNS)
- TLS 1.3: RFC 7924

Different from TLS 1.3 pre-shared symmetric key mode

- PSK is a harder(?) key management problem
- Different compromise model

# Variant: Pre-distributed public keys

- Alternate KEMTLS protocol flow when server certificates are known in advance
- Resumption-style mechanism that avoids the downsides of symmetric-key TLS PSK
- Given server’s long-term key, client can send ciphertext in ClientHello
- Also allow to send client certificate in ClientHello

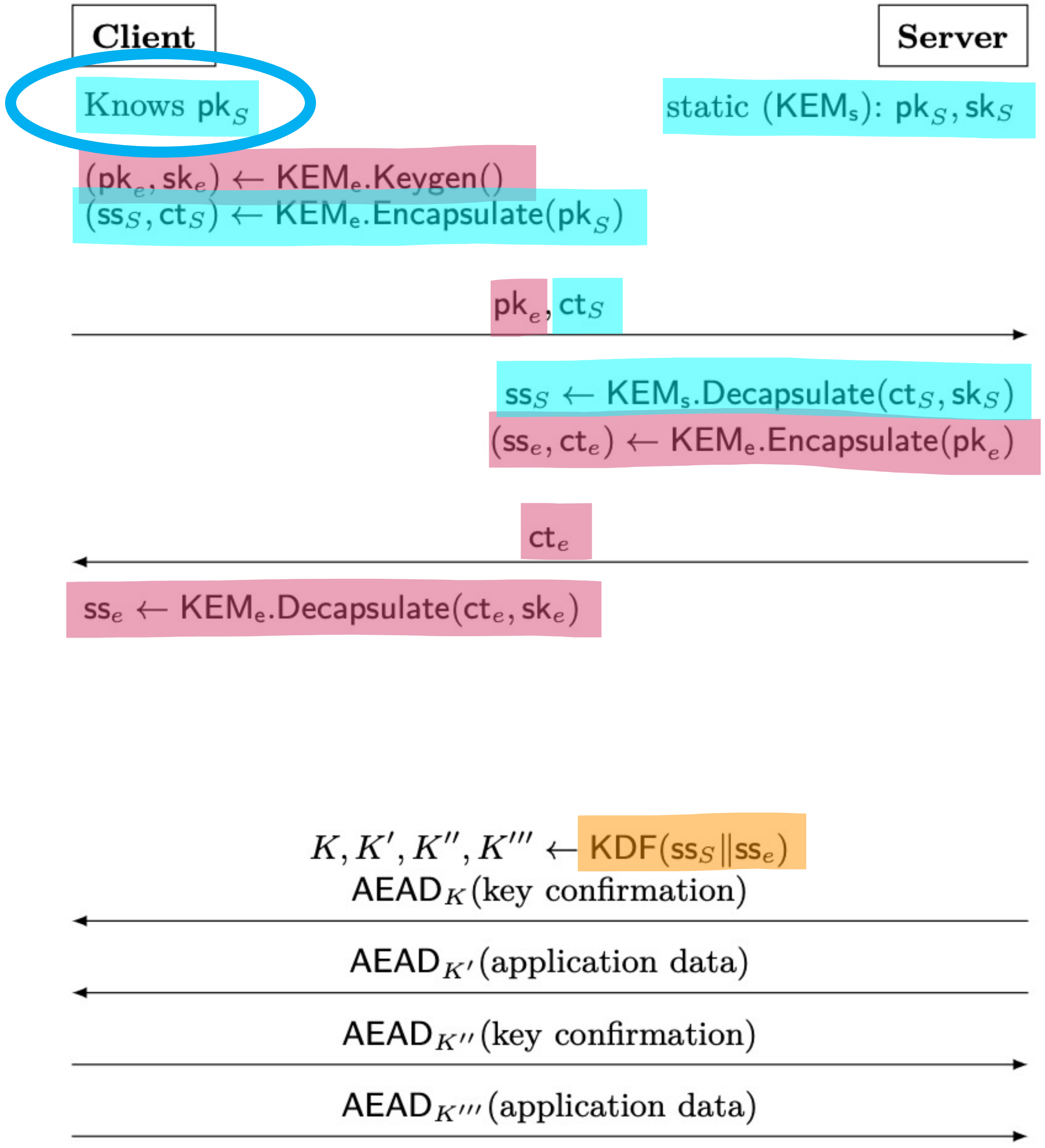
Get a **1-RTT**, TLS 1.3-shape handshake with implicit authentication

# KEMTLS-PDK handshake server-only auth.

KEM for ephemeral key exchange

KEM for server-to-client authenticated key exchange

Combine shared secrets



# KEMTLS-PDK handshake mutual auth

KEM for ephemeral key exchange

KEM for server-to-client authenticated key exchange

KEM for client-to-server authenticated key exchange

Combine shared secrets

**Client** | **Server**

Client: static $(\mathsf{KEM_c})$: $\mathsf{pk}_C, \mathsf{sk}_C$

Server: static $(\mathsf{KEM_s})$: $\mathsf{pk}_S, \mathsf{sk}_S$

Client:

Knows $\mathsf{pk}_S$

$(\mathsf{pk}_e, \mathsf{sk}_e) \leftarrow \mathsf{KEM_e.Keygen}()$

$(\mathsf{ss}_S, \mathsf{ct}_S) \leftarrow \mathsf{KEM_e.Encapsulate}(\mathsf{pk}_S)$

$K_S \leftarrow \mathsf{KDF}(\mathsf{ss}_S)$

$\xrightarrow{\mathsf{pk}_e,\ \mathsf{ct}_S,\ \mathsf{AEAD}_{K_S}(\mathsf{cert}\ [\mathsf{pk}_C])}$

Server:

$\mathsf{ss}_S \leftarrow \mathsf{KEM_s.Decapsulate}(\mathsf{ct}_S, \mathsf{sk}_S)$

$(\mathsf{ss}_e, \mathsf{ct}_e) \leftarrow \mathsf{KEM_e.Encapsulate}(\mathsf{pk}_e)$

$(\mathsf{ss}_C, \mathsf{ct}_C) \leftarrow \mathsf{KEM_c.Encapsulate}(\mathsf{pk}_C)$

$\xleftarrow{\mathsf{ct}_e}$

Client:

$\mathsf{ss}_e \leftarrow \mathsf{KEM_e.Decapsulate}(\mathsf{ct}_e, \mathsf{sk}_e)$

$K_1 \leftarrow \mathsf{KDF}(\mathsf{ss}_S \| \mathsf{ss}_e)$

$\xleftarrow{\mathsf{AEAD}_{K_1}(\mathsf{ct}_C)}$

Client:

$\mathsf{ss}_C \leftarrow \mathsf{KEM_c.Decapsulate}(\mathsf{ct}_C, \mathsf{sk}_C)$

$K_2, K_2', K_2'', K_2''' \leftarrow \mathsf{KDF}(\mathsf{ss}_S \| \mathsf{ss}_e \| \mathsf{ss}_C)$

$\xleftarrow{\mathsf{AEAD}_{K_2}(\text{key confirmation})}$

$\xleftarrow{\mathsf{AEAD}_{K_2'}(\text{application data})}$

$\xrightarrow{\mathsf{AEAD}_{K_2''}(\text{key confirmation})}$

$\xrightarrow{\mathsf{AEAD}_{K_2'''}(\text{application data})}$

# Benefits from pre-distributed key variant

- Additional bandwidth savings
- Makes some PQ algorithms viable
  - Large public keys, small ciphertexts/signatures: Classic McEliece and Rainbow
- Client authentication 1 round-trip earlier if proactive
- Explicit server authentication 1 round-trip earlier
  - => better downgrade resilience

# Other security properties

## Anonymity

- Client certificate encrypted
- Server certificate encrypted
- Server identity not protected
  - Due to Server Name Indication extension
  - May be able to combine KEMTLS-PDK with Encrypted ClientHello?

## Deniability

- KEMTLS and KEMTLS-PDK don’t use signatures for authentication
- Yields offline deniability
  - Judge cannot distinguish honest transcript from forgery
- Does not yield online deniability
  - When one party doesn’t follow protocol or colludes with jduge

# TLS ecosystem is complex – lots to consider!

- Datagram TLS
- Use of TLS handshake in other protocols
  - e.g. QUIC
- Application-specific behaviour
- PKI involving KEM public keys
- Long tail of implementations
- Middle-box behaviour
- …

# X.509 certificates for KEM public keys: Proof of possession

**How does requester prove possession of corresponding secret keys?**

- Interactive challenge-response protocol: RFC 4210 Sect. 5.2.8.3
- Send certificate back encrypted under subject public key RFC 4210 Sect. 5.2.8.2
  - Weird confidentiality requirement on certificate. Maybe broken by Certificate Transparency?
- Non-interactive certificate signing requests: Not a signature scheme!
  - Research in progress: Can build a not-too-inefficient Picnic-like signature scheme from the KEM operation
    - Kyber proof of possession: 227 KB, < 1 sec proof generation and verifcation

# Transitioning the TLS protocol to post-quantum cryptography

Douglas Stebila

UNIVERSITY OF WATERLOO

https://www.douglas.stebila.ca/research/presentations/

## Prototypes

Open Quantum Safe project

https://eprint.iacr.org/2019/1447 • https://openquantumsafe.org • https://github.com/open-quantum-safe/

## Hybrid key exchange in TLS 1.3

Working towards standardization

https://datatracker.ietf.org/doc/html/draft-ietf-tls-hybrid-design-03

## Alternative protocol design: KEMTLS

Implicitly authenticated TLS without handshake signatures using KEMs

- Saves bytes on the wire, server cycles
- Variants for client authentication and pre-distributed public keys
- Lots of work to make viable in TLS ecosystem, including certificates

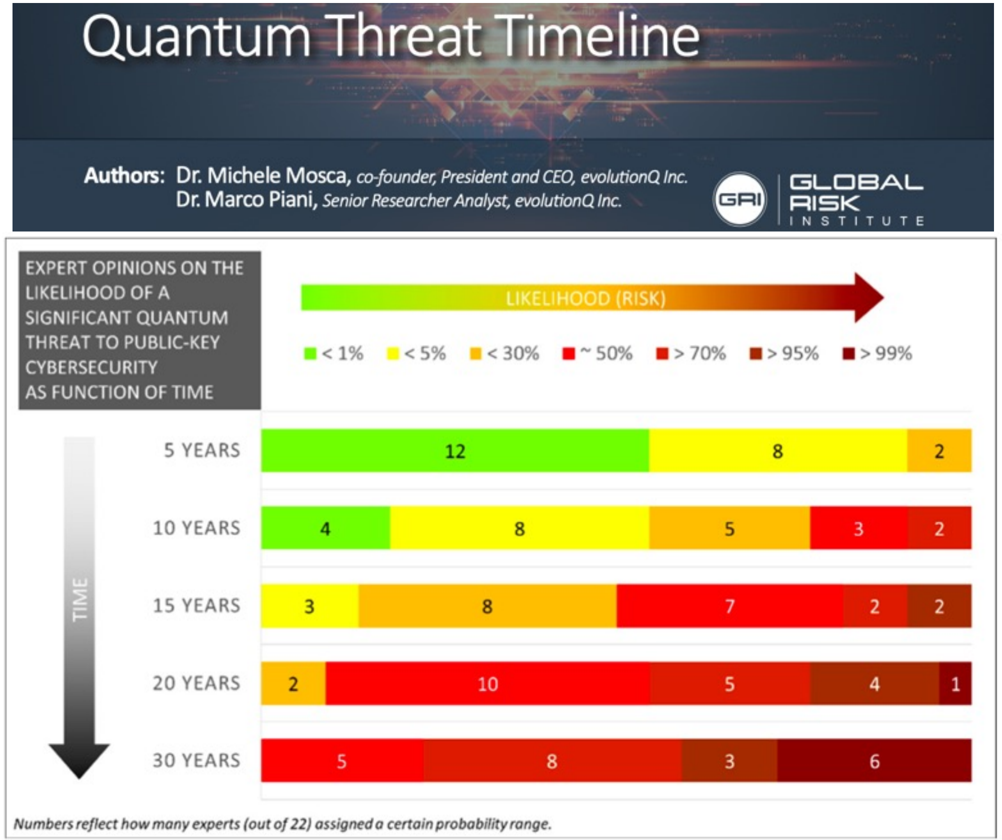
https://eprint.iacr.org/2020/534 • https://eprint.iacr.org/2021/779
https://datatracker.ietf.org/doc/html/draft-celi-wiggers-tls-authkem-00

# Appendix

# When will a large-scale quantum computer be built?

“I estimate a 1/7 chance of breaking RSA-2048 by 2026 and a 1/2 chance by 2031.”

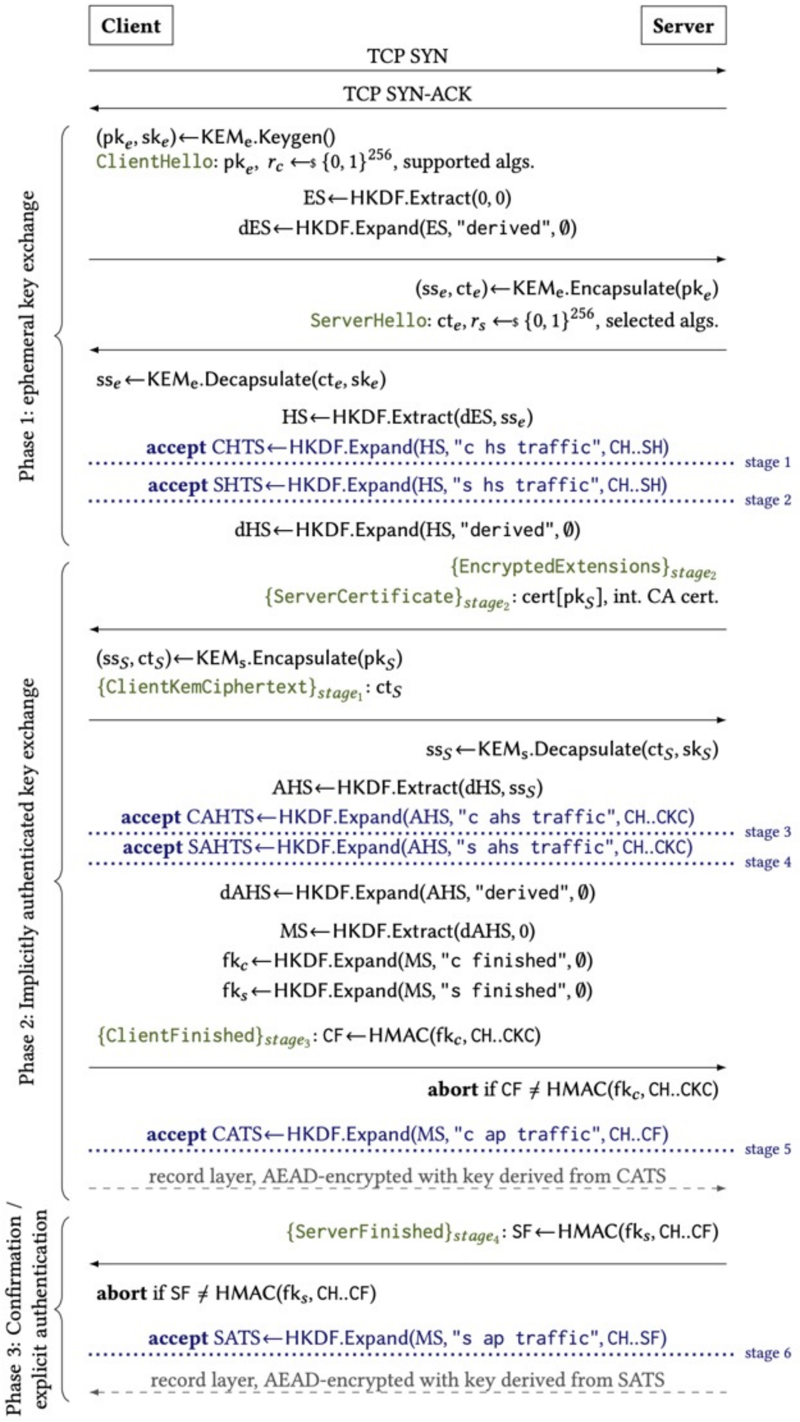
— Michele Mosca,
University of Waterloo


https://eprint.iacr.org/2015/1075
http://qurope.eu/system/files/u7/93056_Quantum%20Manifesto_WEB.pdf
https://globalriskinstitute.org/publications/quantum-threat-timeline/

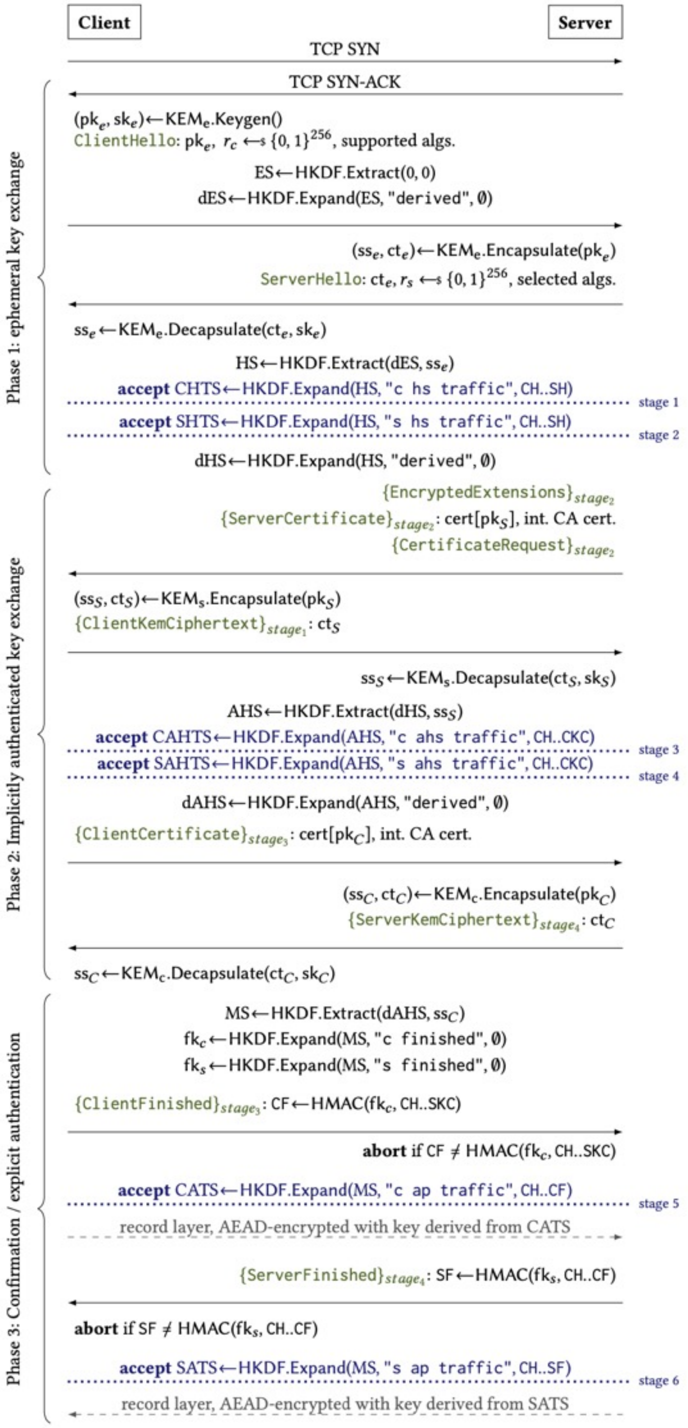
# Appendix: KEMTLS

# KEMTLS



Client
Server
TCP SYN
TCP SYN-ACK
Phase 1: ephemeral key exchange
(pk_e, sk_e) ← KEM_e.Keygen()
ClientHello: pk_e, r_c ←$ {0, 1}^256, supported algs.
ES ← HKDF.Extract(0, 0)
dES ← HKDF.Expand(ES, "derived", ∅)
(ss_e, ct_e) ← KEM_e.Encapsulate(pk_e)
ServerHello: ct_e, r_s ←$ {0, 1}^256, selected algs.
ss_e ← KEM_e.Decapsulate(ct_e, sk_e)
HS ← HKDF.Extract(dES, ss_e)
accept CHTS ← HKDF.Expand(HS, "c hs traffic", CH..SH)
stage 1
accept SHTS ← HKDF.Expand(HS, "s hs traffic", CH..SH)
stage 2
dHS ← HKDF.Expand(HS, "derived", ∅)
Phase 2: Implicitly authenticated key exchange
{EncryptedExtensions}_stage2
{ServerCertificate}_stage2: cert[pk_S], int. CA cert.
(ss_S, ct_S) ← KEM_s.Encapsulate(pk_S)
{ClientKemCiphertext}_stage1: ct_S
ss_S ← KEM_s.Decapsulate(ct_S, sk_S)
AHS ← HKDF.Extract(dHS, ss_S)
accept CAHTS ← HKDF.Expand(AHS, "c ahs traffic", CH..CKC)
stage 3
accept SAHTS ← HKDF.Expand(AHS, "s ahs traffic", CH..CKC)
stage 4
dAHS ← HKDF.Expand(AHS, "derived", ∅)
MS ← HKDF.Extract(dAHS, 0)
fk_c ← HKDF.Expand(MS, "c finished", ∅)
fk_s ← HKDF.Expand(MS, "s finished", ∅)
{ClientFinished}_stage3: CF ← HMAC(fk_c, CH..CKC)
abort if CF ≠ HMAC(fk_c, CH..CKC)
accept CATS ← HKDF.Expand(MS, "c ap traffic", CH..CF)
stage 5
record layer, AEAD-encrypted with key derived from CATS
Phase 3: Confirmation / explicit authentication
{ServerFinished}_stage4: SF ← HMAC(fk_s, CH..CF)
abort if SF ≠ HMAC(fk_s, CH..CF)
accept SATS ← HKDF.Expand(MS, "s ap traffic", CH..SF)
stage 6
record layer, AEAD-encrypted with key derived from SATS

# KEMTLS
# with client authentication



# TLS 1.3 and KEMTLS size of public key objects

| | | | | Excluding intermediate CA certificate | | | | Including intermediate CA certificate | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Abbrv. | KEX (pk+ct) | HS auth (ct/sig) | Leaf crt. subject (pk) | Leaf crt. (signature) | Sum excl. int. CA cert. | Int. CA crt. subject (pk) | Int. CA crt. (signature) | Sum incl. int. CA crt. | Root CA (pk) | Sum TCP pay-loads of TLS HS (incl. int. CA crt.) |
| TLS 1.3 (Signed KEX) | **TLS 1.3** | errr | ECDH (X25519) 64 | RSA-2048 256 | RSA-2048 272 | RSA-2048 256 | **848** | RSA-2048 272 | RSA-2048 256 | **1376** | RSA-2048 272 | 2829 |
| | **Min. incl. int. CA cert.** | SFXR | SIKE 433 | Falcon 690 | Falcon 897 | $XMSS_s^{MT}$ 979 | **2999** | $XMSS_s^{MT}$ 32 | Rainbow 66 | **3097** | Rainbow 161600 | 5378 |
| | **Min. excl. int. CA cert.** | SFRR | SIKE 433 | Falcon 690 | Falcon 897 | Rainbow 66 | **2086** | Rainbow 60192 | Rainbow 66 | **62344** | Rainbow 60192 | 64693 |
| | **Assumption: MLWE+MSIS** | KDDD | Kyber 1568 | Dilithium 2420 | Dilithium 1312 | Dilithium 2420 | **7720** | Dilithium 1312 | Dilithium 2420 | **11452** | Dilithium 1312 | 12639 |
| | **Assumption: NTRU** | NFFF | NTRU 1398 | Falcon 690 | Falcon 897 | Falcon 690 | **3675** | Falcon 897 | Falcon 690 | **5262** | Falcon 897 | 6524 |
| KEMTLS | **Min. incl. int. CA cert.** | SSXR | SIKE 433 | SIKE 236 | SIKE 197 | $XMSS_s^{MT}$ 979 | **1845** | $XMSS_s^{MT}$ 32 | Rainbow 66 | **1943** | Rainbow 60192 | 4252 |
| | **Min. excl. int. CA cert.** | SSRR | SIKE 433 | SIKE 236 | SIKE 197 | Rainbow 66 | **932** | Rainbow 60192 | Rainbow 66 | **61190** | Rainbow 60192 | 63568 |
| | **Assumption: MLWE+MSIS** | KKDD | Kyber 1568 | Kyber 768 | Kyber 800 | Dilithium 2420 | **5556** | Dilithium 1312 | Dilithium 2420 | **9288** | Dilithium 1312 | 10471 |
| | **Assumption: NTRU** | NNFF | NTRU 1398 | NTRU 699 | NTRU 699 | Falcon 690 | **3486** | Falcon 897 | Falcon 690 | **5073** | Falcon 897 | 6359 |

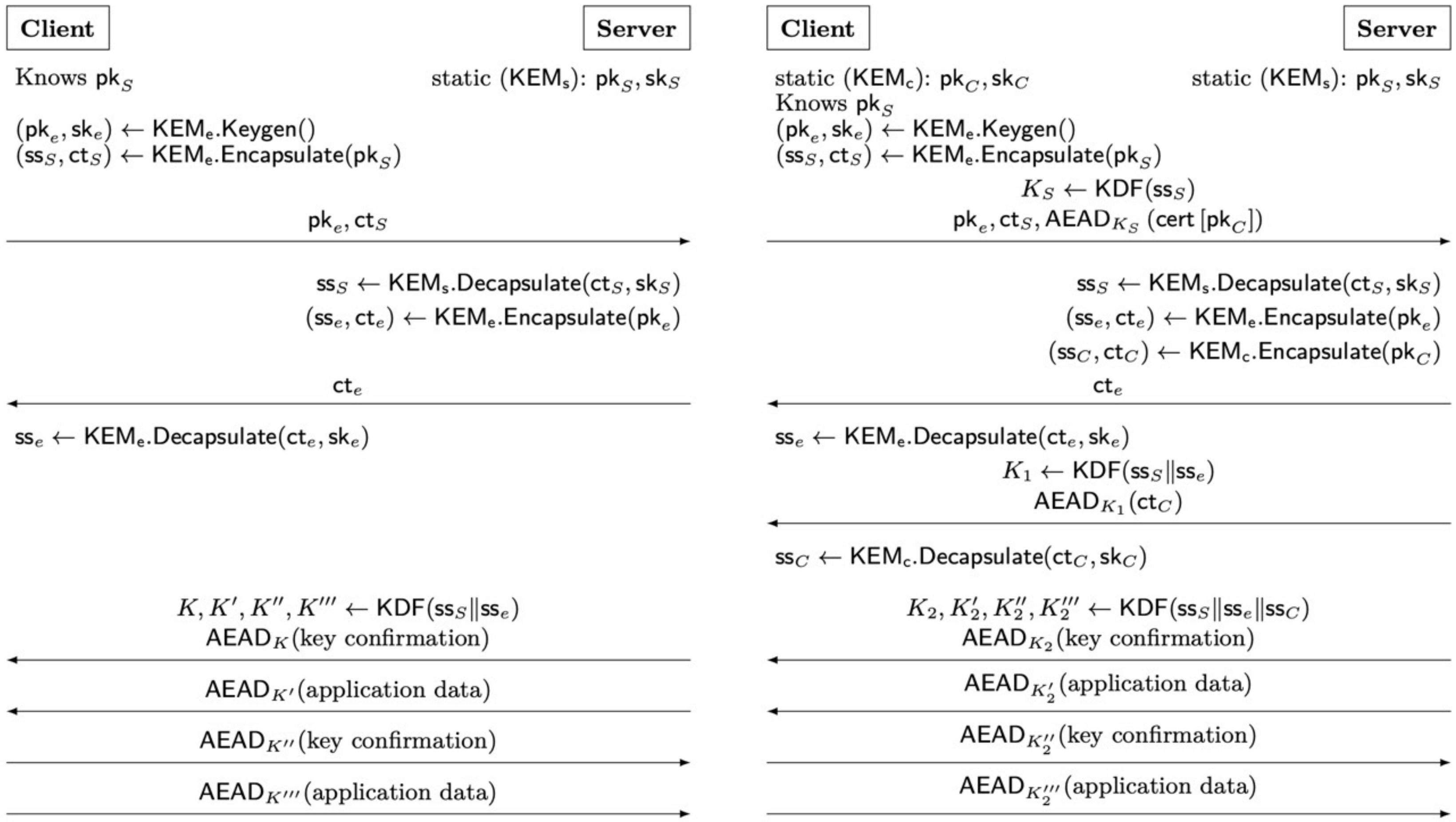
# TLS 1.3 and KEMTLS crypto & handshake time

| | | Computation time for asymmetric crypto | | | | Handshake time (31.1 ms latency, 1000 Mbps bandwidth) | | | | | | Handshake time (195.6 ms latency, 10 Mbps bandwidth) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Excl. int. CA cert. | | Incl. int. CA cert. | | Excl. int. CA cert. | | | Incl. int. CA cert. | | | Excl. int. CA cert. | | | Incl. int. CA cert. | | |
| | | Client | Server | Client | Server | Client sent req. | Client recv. resp. | Server HS done | Client sent req. | Client recv. resp. | Server HS done | Client sent req. | Client recv. resp. | Server HS done | Client sent req. | Client recv. resp. | Server HS done |
| TLS 1.3 | **errr** | 0.134 | 0.629 | 0.150 | 0.629 | 66.4 | **97.7** | 35.5 | 66.5 | **97.7** | 35.5 | 397.3 | **593.4** | 201.4 | 398.3 | **594.5** | 202.4 |
| | **SFXR** | 11.860 | 4.410 | 12.051 | 4.410 | 80.1 | **111.3** | 49.2 | 80.4 | **111.5** | 49.4 | 417.5 | **615.0** | 218.9 | 417.4 | **614.9** | 219.1 |
| | **SFRR** | 6.061 | 4.410 | 6.251 | 4.410 | 65.5 | **96.7** | 34.5 | 131.4 | **162.6** | 100.4 | 398.3 | **594.6** | 201.8 | 1846.8 | **2244.5** | 1578.7 |
| | **KDDD** | 0.059 | 0.072 | 0.081 | 0.072 | 63.8 | **95.1** | 32.9 | 64.1 | **95.4** | 33.2 | 405.1 | **602.3** | 208.3 | 410.3 | **609.8** | 212.8 |
| | **NFFF** | 0.138 | 0.241 | 0.180 | 0.241 | 64.8 | **96.0** | 33.8 | 65.1 | **96.4** | 34.2 | 397.8 | **593.9** | 201.2 | 399.8 | **596.0** | 203.2 |
| KEMTLS | **SSXR** | 15.998 | 7.173 | 16.188 | 7.173 | 84.5 | **124.6** | 62.5 | 84.3 | **124.4** | 62.3 | 417.5 | **625.8** | 232.5 | 417.6 | **625.8** | 232.4 |
| | **SSRR** | 10.198 | 7.173 | 10.388 | 7.173 | 75.5 | **116.3** | 54.2 | 140.3 | **182.3** | 120.1 | 408.5 | **616.5** | 223.5 | 1684.2 | **2091.6** | 1280.4 |
| | **KKDD** | 0.048 | 0.017 | 0.070 | 0.017 | 63.3 | **94.8** | 32.6 | 63.7 | **95.2** | 32.9 | 397.3 | **594.4** | 201.6 | 434.7 | **638.0** | 235.4 |
| | **NNFF** | 0.107 | 0.021 | 0.149 | 0.021 | 63.4 | **95.0** | 32.7 | 63.7 | **95.3** | 33.0 | 395.9 | **593.0** | 200.1 | 397.6 | **594.7** | 201.9 |

Label syntax: ABCD: A = ephemeral key exchange, B = leaf certificate, C = intermediate CA certificate, D = root certificate.

Label values: Dilithium, eCDH X25519, Falcon, Kyber, NTRU, Rainbow, rSA-2048, SIKE, $XMSS_s^{MT}$; all level-1 schemes.

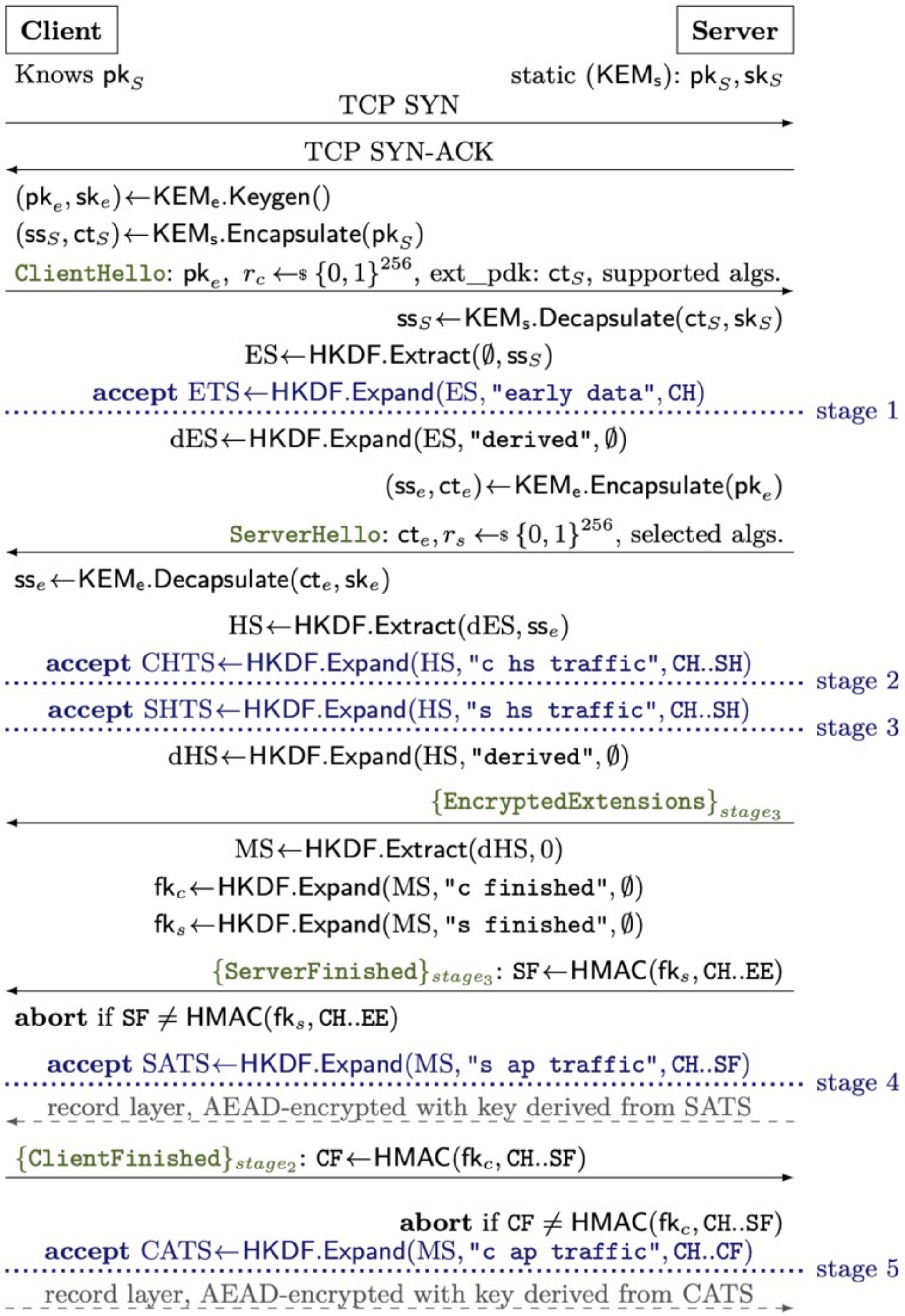
# KEMTLS-PDK overview




(a) Unilaterally authenticated

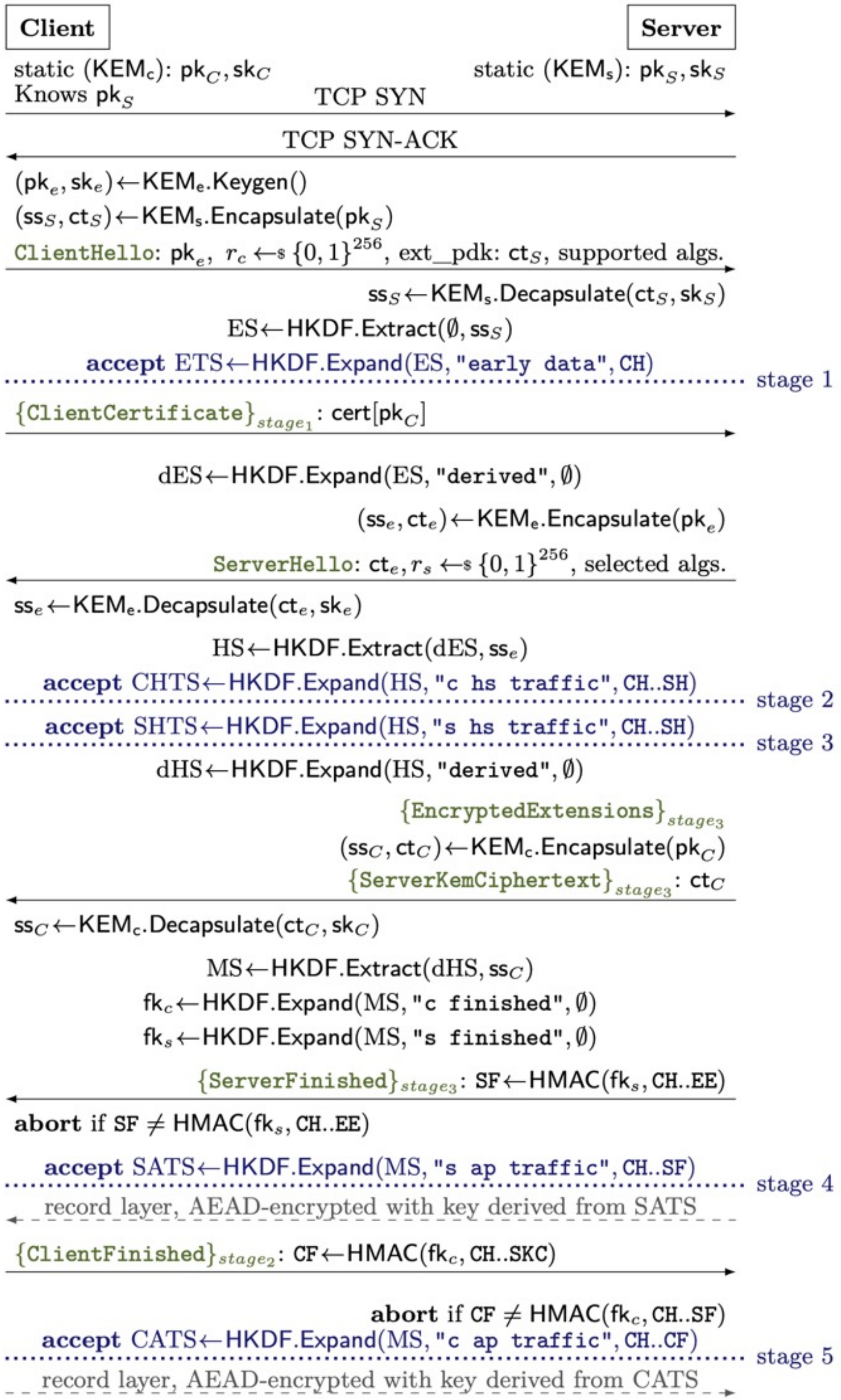
(b) With proactive client authentication

# KEMTLS-PDK



Client
Server
Knows $\mathsf{pk}_S$
static ($\mathsf{KEM_s}$): $\mathsf{pk}_S, \mathsf{sk}_S$
TCP SYN
TCP SYN-ACK
$(\mathsf{pk}_e, \mathsf{sk}_e) \leftarrow \mathsf{KEM_e.Keygen}()$
$(\mathsf{ss}_S, \mathsf{ct}_S) \leftarrow \mathsf{KEM_s.Encapsulate}(\mathsf{pk}_S)$
ClientHello: $\mathsf{pk}_e$, $r_c \leftarrow_\$ \{0,1\}^{256}$, ext_pdk: $\mathsf{ct}_S$, supported algs.
$\mathsf{ss}_S \leftarrow \mathsf{KEM_s.Decapsulate}(\mathsf{ct}_S, \mathsf{sk}_S)$
$\mathrm{ES} \leftarrow \mathsf{HKDF.Extract}(\emptyset, \mathsf{ss}_S)$
accept $\mathrm{ETS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ES}, \texttt{"early data"}, \texttt{CH})$
stage 1
$\mathrm{dES} \leftarrow \mathsf{HKDF.Expand}(\mathrm{ES}, \texttt{"derived"}, \emptyset)$
$(\mathsf{ss}_e, \mathsf{ct}_e) \leftarrow \mathsf{KEM_e.Encapsulate}(\mathsf{pk}_e)$
ServerHello: $\mathsf{ct}_e, r_s \leftarrow_\$ \{0,1\}^{256}$, selected algs.
$\mathsf{ss}_e \leftarrow \mathsf{KEM_e.Decapsulate}(\mathsf{ct}_e, \mathsf{sk}_e)$
$\mathrm{HS} \leftarrow \mathsf{HKDF.Extract}(\mathrm{dES}, \mathsf{ss}_e)$
accept $\mathrm{CHTS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HS}, \texttt{"c hs traffic"}, \texttt{CH..SH})$
stage 2
accept $\mathrm{SHTS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HS}, \texttt{"s hs traffic"}, \texttt{CH..SH})$
stage 3
$\mathrm{dHS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{HS}, \texttt{"derived"}, \emptyset)$
$\{\texttt{EncryptedExtensions}\}_{stage_3}$
$\mathrm{MS} \leftarrow \mathsf{HKDF.Extract}(\mathrm{dHS}, 0)$
$\mathsf{fk}_c \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \texttt{"c finished"}, \emptyset)$
$\mathsf{fk}_s \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \texttt{"s finished"}, \emptyset)$
$\{\texttt{ServerFinished}\}_{stage_3}$: $\texttt{SF} \leftarrow \mathsf{HMAC}(\mathsf{fk}_s, \texttt{CH..EE})$
abort if $\texttt{SF} \neq \mathsf{HMAC}(\mathsf{fk}_s, \texttt{CH..EE})$
accept $\mathrm{SATS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \texttt{"s ap traffic"}, \texttt{CH..SF})$
stage 4
record layer, AEAD-encrypted with key derived from SATS
$\{\texttt{ClientFinished}\}_{stage_2}$: $\texttt{CF} \leftarrow \mathsf{HMAC}(\mathsf{fk}_c, \texttt{CH..SF})$
abort if $\texttt{CF} \neq \mathsf{HMAC}(\mathsf{fk}_c, \texttt{CH..SF})$
accept $\mathrm{CATS} \leftarrow \mathsf{HKDF.Expand}(\mathrm{MS}, \texttt{"c ap traffic"}, \texttt{CH..CF})$
stage 5
record layer, AEAD-encrypted with key derived from CATS

# KEMTLS-PDK with proactive client authentication



| | KEMTLS | Cached TLS | KEMTLS-PDK |
|---|---|---|---|
| *Unilaterally authenticated* | | | |
| Round trips until client receives response data | 3 | 3 | 3 |
| Size (bytes) of public key crypto objects transmitted: | | | |
| • Minimum PQ | 932 | 499 | 561 |
| • Module-LWE/Module-SIS (Kyber, Dilithium) | 5,556 | 3,988 | 2,336 |
| • NTRU-based (NTRU, Falcon) | 3,486 | 2,088 | 2,144 |
| *Mutually authenticated* | | | |
| Round trips until client receives response data | $\boxed{4}$ | 3 | $\boxed{3}$ |
| Size (bytes) of public key crypto objects transmitted: | | | |
| • Minimum PQ | 1,431 | 2,152 | 1,060 |
| • MLWE/MSIS | 9,554 | 10,140 | 6,324 |
| • NTRU | 5,574 | 4,365 | 4,185 |

# Communication sizes

KEMTLS

TLS 1.3 w/cached server certs

KEMTLS-PDK

| | | Transmitted Ephem. (pk+ct) | Transmitted Auth | Sum | Client Auth Cert. (pk+ct/sig) | Client Auth CA (sig) | Sum (total) | Cached Leaf pk | Cached Cl. Auth CA (pk) |
|---|---|---|---|---|---|---|---|---|---|
| KEMTLS | Minimum | SIKE 197 236 | SIKE/Rai. crt+ct 499 | **932** | SIKE 433 | Rainbow 66 | **1,431** | N/A | Rainbow 161,600 |
| KEMTLS | Assumption: MLWE/MSIS | Kyber 800 768 | Kyber/Dil. crt+ct 3,988 | **5,556** | Kyber 1,568 | Dilithium 2,420 | **9,554** | N/A | Dilithium 1,312 |
| KEMTLS | Assumption: NTRU | NTRU 699 699 | NTRU/Fal. crt+ct 2,088 | **3,486** | NTRU 1,398 | Falcon 690 | **5,574** | N/A | Falcon 897 |
| Cached TLS | TLS 1.3 | X25519 32 32 | RSA-2048 sig 256 | **320** | RSA-2048 528 | RSA-2048 256 | **1,104** | RSA-2048 272 | RSA-2048 272 |
| Cached TLS | Minimum | SIKE 197 236 | Rainbow sig 66 | **499** | Falcon 1,587 | Rainbow 66 | **2,152** | Rainbow 161,600 | Rainbow 161,600 |
| Cached TLS | Assumption: MLWE/MSIS | Kyber 800 768 | Dilithium sig 2,420 | **3,988** | Dilithium 3,732 | Dilithium 2,420 | **10,140** | Dilithium 1,312 | Dilithium 1,312 |
| Cached TLS | Assumption: NTRU | NTRU 699 699 | Falcon sig 690 | **2,088** | Falcon 1,587 | Falcon 690 | **4,365** | Falcon 897 | Falcon 897 |
| KEMTLS-PDK | Minimum | SIKE 197 236 | McEliece ct 128 | **561** | SIKE 433 | Rainbow 66 | **1,060** | McEliece 261,120 | Rainbow 161,600 |
| KEMTLS-PDK | Finalist: Kyber | Kyber 800 768 | Kyber ct 768 | **2,336** | Kyber 1,568 | Dilithium 2,420 | **6,324** | Kyber 800 | Dilithium 1,312 |
| KEMTLS-PDK | Finalist: NTRU | NTRU 699 699 | NTRU ct 699 | **2,097** | NTRU 1,398 | Falcon 690 | **4,185** | NTRU 699 | Falcon 897 |
| KEMTLS-PDK | Finalist: SABER | SABER 672 736 | SABER ct 736 | **2,144** | SABER 1,408 | Dilithium 2,420 | **5,972** | SABER 672 | Dilithium 1,312 |

# Handshake times, unilateral authentication

| Unilaterally authenticated | | 31.1 ms RTT, 1000 Mbps | | | 195.6 ms RTT, 10 Mbps | | |
|---|---|---|---|---|---|---|---|
| | | Client sent req. | Client recv. resp. | Server expl. auth. | Client sent req. | Client recv. resp. | Server expl. auth. |
| KEMTLS | Minimum | 75.4 | **116.1** | 116.1 | 408.6 | **616.3** | 616.2 |
| | MLWE/MSIS | 63.2 | **94.8** | 94.7 | 397.4 | **594.6** | 594.5 |
| | NTRU | 63.1 | **94.7** | 94.6 | 396.0 | **593.0** | 593.0 |
| Cached TLS | TLS 1.3 | 66.4 | **97.6** | 66.3 | 396.8 | **592.9** | 396.7 |
| | Minimum | 70.1 | **101.3** | 70.0 | 402.3 | **598.5** | 402.2 |
| | MLWE/MSIS | 63.9 | **95.1** | 63.8 | 397.2 | **593.4** | 397.1 |
| | NTRU | 64.8 | **96.1** | 64.7 | 397.0 | **593.2** | 396.9 |
| PDK | Minimum | 66.3 | **97.5** | 66.2 | 397.9 | **594.1** | 397.8 |
| | Kyber | 63.1 | **94.3** | 63.0 | 395.3 | **591.4** | 395.2 |
| | NTRU | 63.1 | **94.3** | 63.0 | 395.3 | **591.5** | 395.2 |
| | SABER | 63.1 | **94.3** | 63.0 | 395.2 | **591.4** | 395.2 |

# Handshake times, mutual authentication

| Mutually authenticated | | 31.1 ms RTT, 1000 Mbps Client sent req. | Client recv. resp. | Server expl. auth. | 195.6 ms RTT, 10 Mbps Client sent req. | Client recv. resp. | Server expl. auth. |
|---|---|---|---|---|---|---|---|
| KEMTLS | Minimum | 130.2 | **161.4** | 161.3 | 631.2 | **827.5** | 827.5 |
| | MLWE/MSIS | 95.2 | **126.6** | 126.6 | 598.3 | **794.6** | 794.6 |
| | NTRU | 95.0 | **126.4** | 126.3 | 595.3 | **791.7** | 791.7 |
| Cached TLS | TLS 1.3 | 68.3 | **99.8** | 65.9 | 399.4 | **597.2** | 396.7 |
| | Minimum | 71.1 | **102.7** | 69.9 | 403.3 | **602.0** | 402.0 |
| | MLWE/MSIS | 64.5 | **96.2** | 63.9 | 400.1 | **616.8** | 399.5 |
| | NTRU | 66.2 | **98.1** | 64.8 | 398.3 | **597.7** | 397.0 |
| PDK | Minimum | 84.9 | **116.1** | 84.9 | 420.5 | **616.8** | 420.5 |
| | Kyber | 63.5 | **94.7** | 63.4 | 400.2 | **596.5** | 400.2 |
| | NTRU | 63.6 | **94.9** | 63.6 | 397.6 | **593.8** | 397.5 |
| | SABER | 63.6 | **94.8** | 63.5 | 399.4 | **595.5** | 399.3 |

# OPEN QUANTUM SAFE

*software for prototyping quantum-resistant cryptography*

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

# liboqs

- C library with common API for post-quantum signature schemes and key encapsulation mechanisms
- MIT License
- Builds on Windows, macOS, Linux; x86_64, ARM v8
- Version 0.7.1 to be released in December 2021
- Includes all Round 3 finalists and alternate candidates
  - (except GeMSS)

https://openquantumsafe.org/liboqs/

# TLS 1.3 implementations

| | OQS-OpenSSL 1.1.1 | OQS-OpenSSL 3 provider | OQS-BoringSSL |
|---|---|---|---|
| PQ key exchange in TLS 1.3 | Yes | Yes | Yes |
| Hybrid key exchange in TLS 1.3 | Yes | Coming soon | Yes |
| PQ certificates and signature authentication in TLS 1.3 | Yes | No | Yes |
| Hybrid certificates and signature authentication in TLS 1.3 | Yes | No | No |

Using draft-ietf-tls-hybrid-design for hybrid key exchange

Interoperability test server running at https://test.openquantumsafe.org

https://openquantumsafe.org/applications/tls/

# Applications

- Demonstrator application integrations into:
  - Apache
  - nginx
  - haproxy
  - curl
  - Chromium
  - Wireshark

- In most cases required few/no modifications to work with updated OpenSSL

- Runnable Docker images available for download

https://openquantumsafe.org/applications/tls/#demo-integrations

# Benchmarking

- Benchmarking portal at https://openquantumsafe.org/benchmarking/

- Core algorithm speed and memory usage
- TLS performance in ideal network conditions
- Intel AVX2 and ARM 64