# Transitioning the TLS protocol to post-quantum security


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NSERC CRSNG

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

University of Surrey • 2021-09-23

UNIVERSITY OF WATERLOO


IQC Institute for Quantum Computing

CYBER SECURITY AND PRIVACY INSTITUTE

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# Cryptography @ University of Waterloo

- UW involved in 4 NIST PQC Round 3 submissions:
  - Finalists: CRYSTALS-Kyber, NTRU
  - Alternates: FrodoKEM, SIKE
- Elliptic curves: David Jao, Alfred Menezes, (Scott Vanstone)
- More cryptography: Sergey Gorbunov, Mohammad Hajiabadi, Doug Stinson
- Privacy-enhancing technologies: Ian Goldberg
- Quantum cryptanalysis: Michele Mosca
- Quantum cryptography: Norbert Lütkenhaus, Thomas Jennewein, Debbie Leung
- Even more cryptography and security: Gord Agnew, Vijay Ganesh, Guang Gong, Sergey Gorbunov, Anwar Hasan, Florian Kerschbaum

# Background

University of Surrey

surrey.ac.uk

Latest coronavirus advice for current and prospective students, staff, partners and visitors: see our coronavirus website

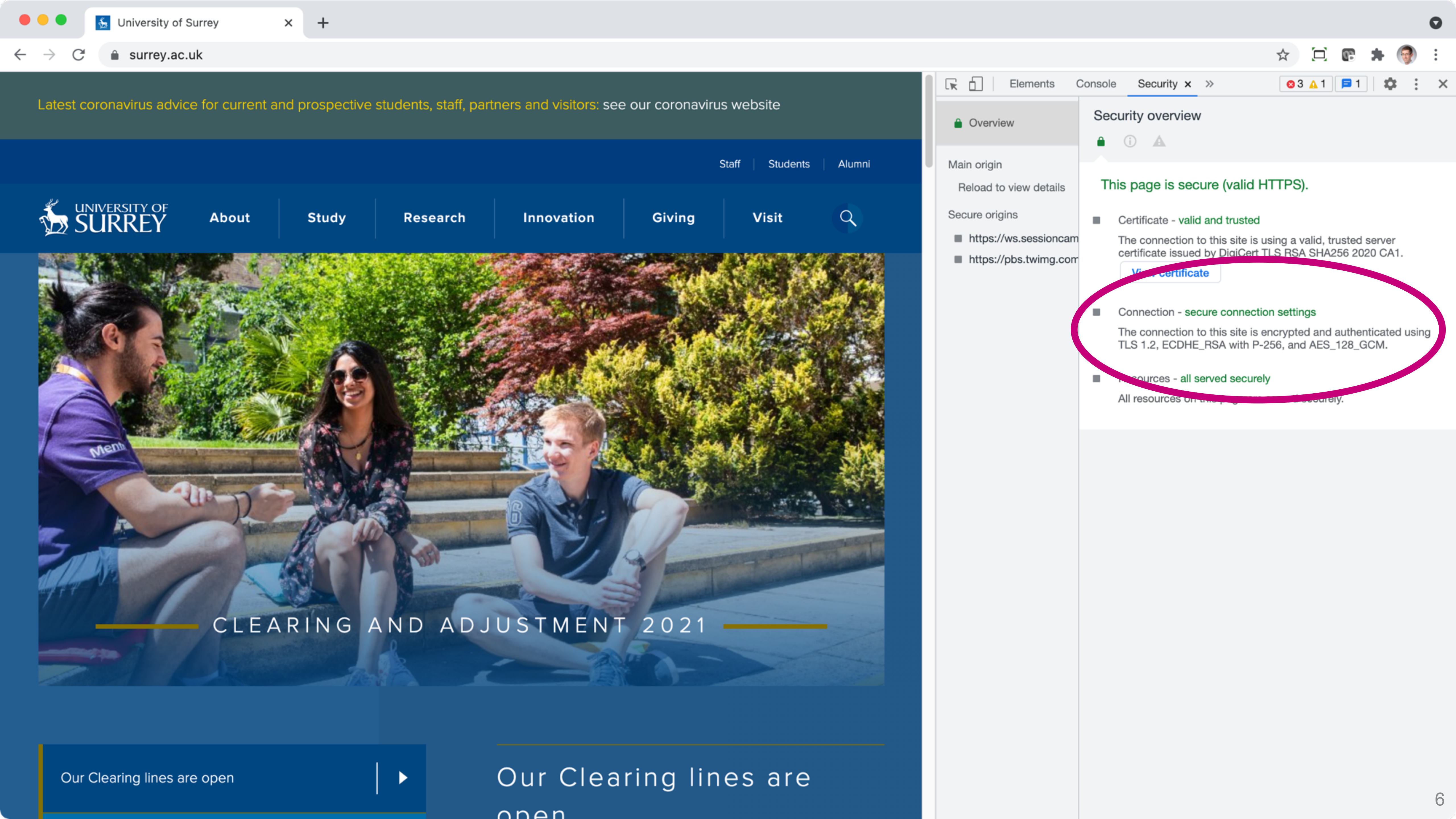
Staff | Students | Alumni

UNIVERSITY OF SURREY

About | Study | Research | Innovation | Giving | Visit


Our Clearing lines are open

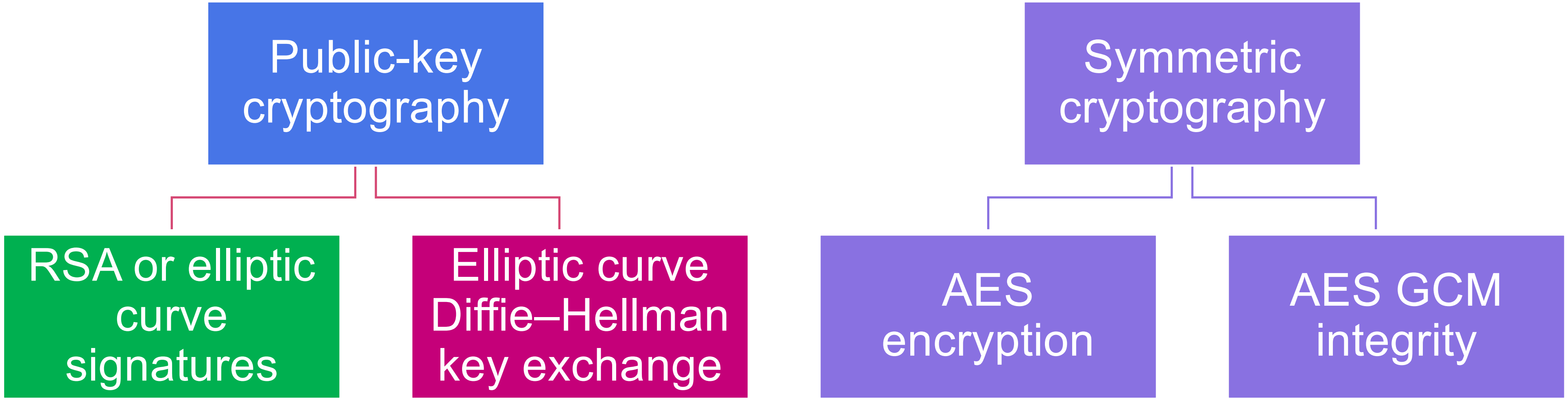
# Our Clearing lines are open


University of Surrey
surrey.ac.uk
Latest coronavirus advice for current and prospective students, staff, partners and visitors: see our coronavirus website
Staff | Students | Alumni
UNIVERSITY OF SURREY
About
Study
Research
Innovation
Giving
Visit
CLEARING AND ADJUSTMENT 2021
Our Clearing lines are open
Our Clearing lines are open
Elements
Console
Security
Overview
Main origin
Reload to view details
Secure origins
https://ws.sessioncam
https://pbs.twimg.com
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 DigiCert TLS RSA SHA256 2020 CA1.
View certificate
Connection - secure connection settings
The connection to this site is encrypted and authenticated using TLS 1.2, ECDHE_RSA with P-256, and AES_128_GCM.
Resources - all served securely
All resources on this page are served securely.

# Cryptographic building blocks

Connection - secure connection settings

The connection to this site is encrypted and authenticated using TLS 1.2, ECDHE_RSA with P-256, and AES_128_GCM.

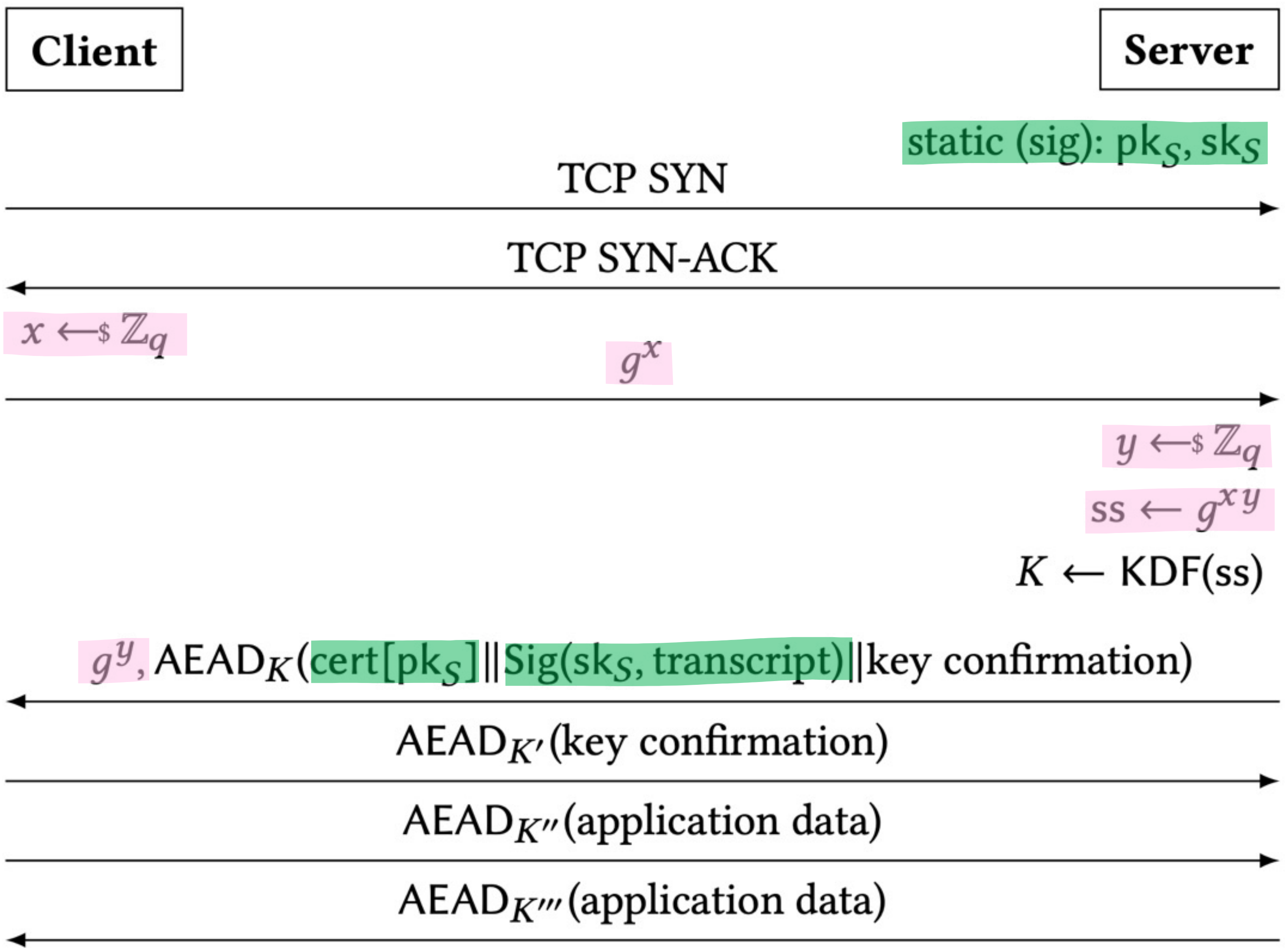


# TLS 1.3 handshake

Diffie-Hellman key exchange

Digital signature

Signed Diffie–Hellman



# Cryptographic building blocks

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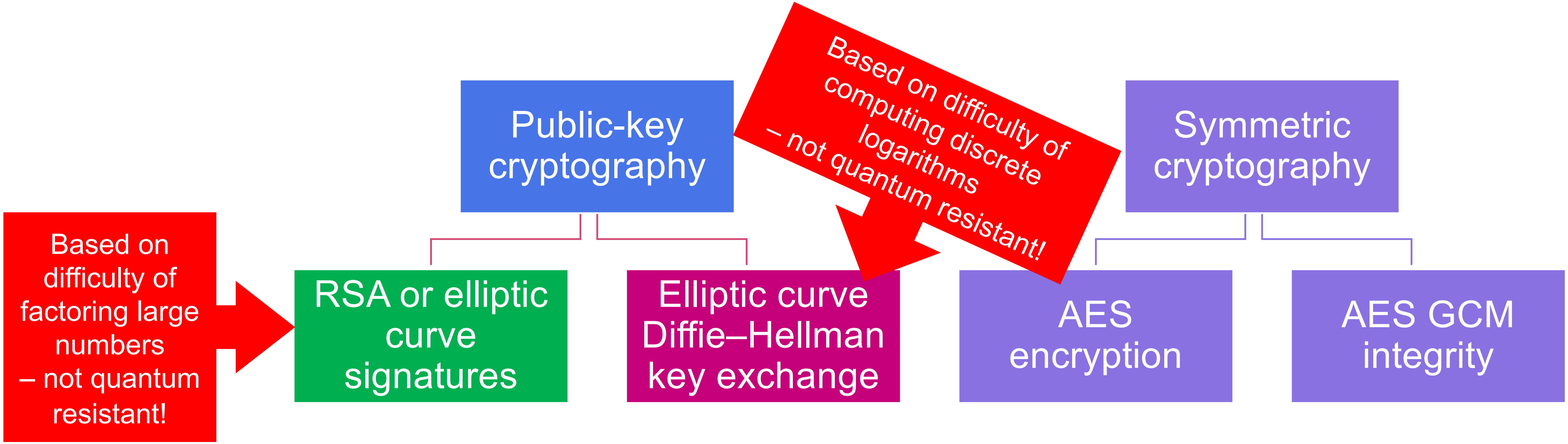
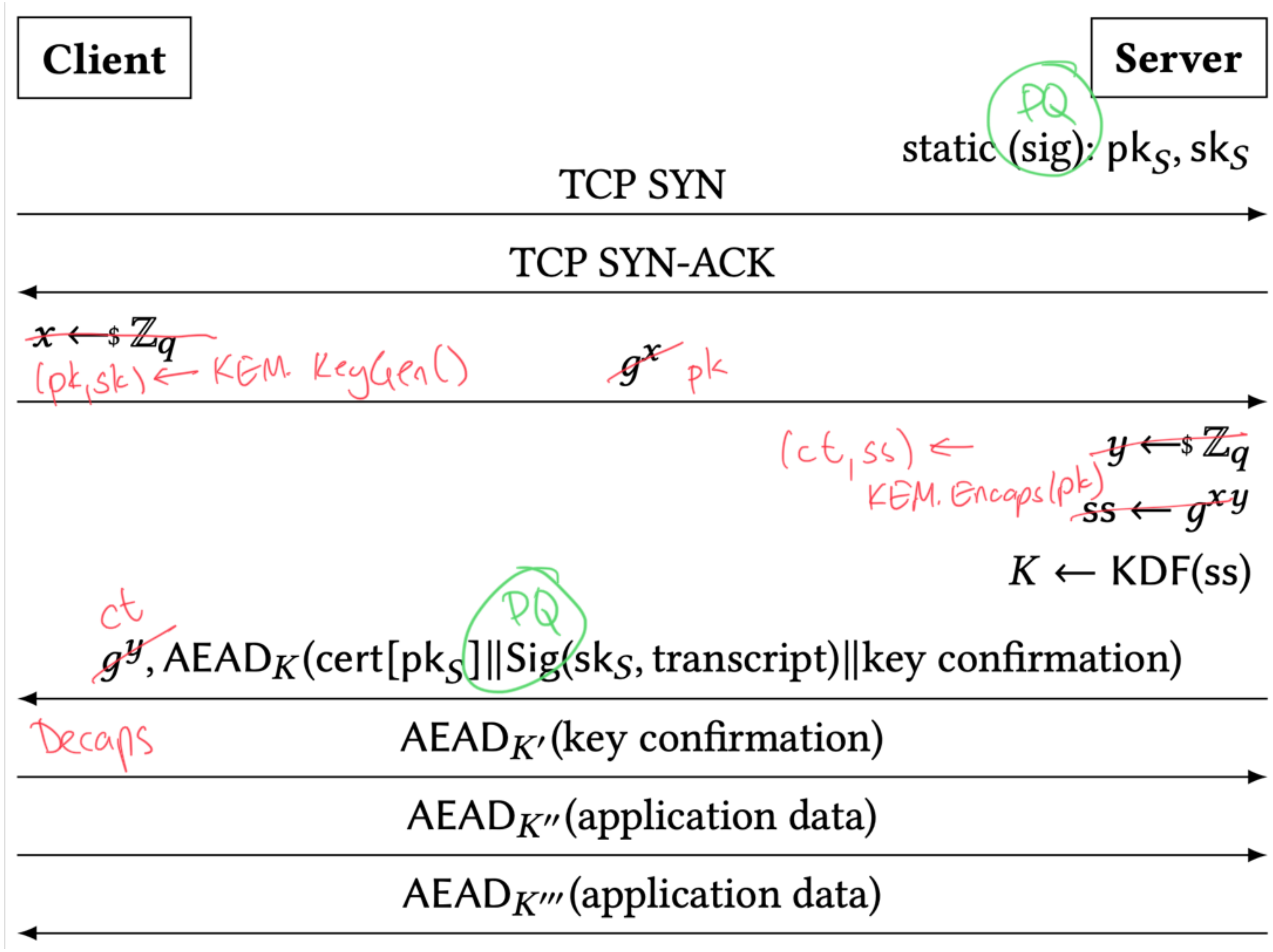


# TLS 1.3 handshake

~~Signed Diffie–Hellman~~

Post-Quantum!!!



# Outline

Post-quantum

Benchmarking

Hybrid standardization

New protocol designs (KEMTLS)

# Why post-quantum?

# Quantum threat to information security

Large-scale general-purpose quantum computers could break some encryption schemes

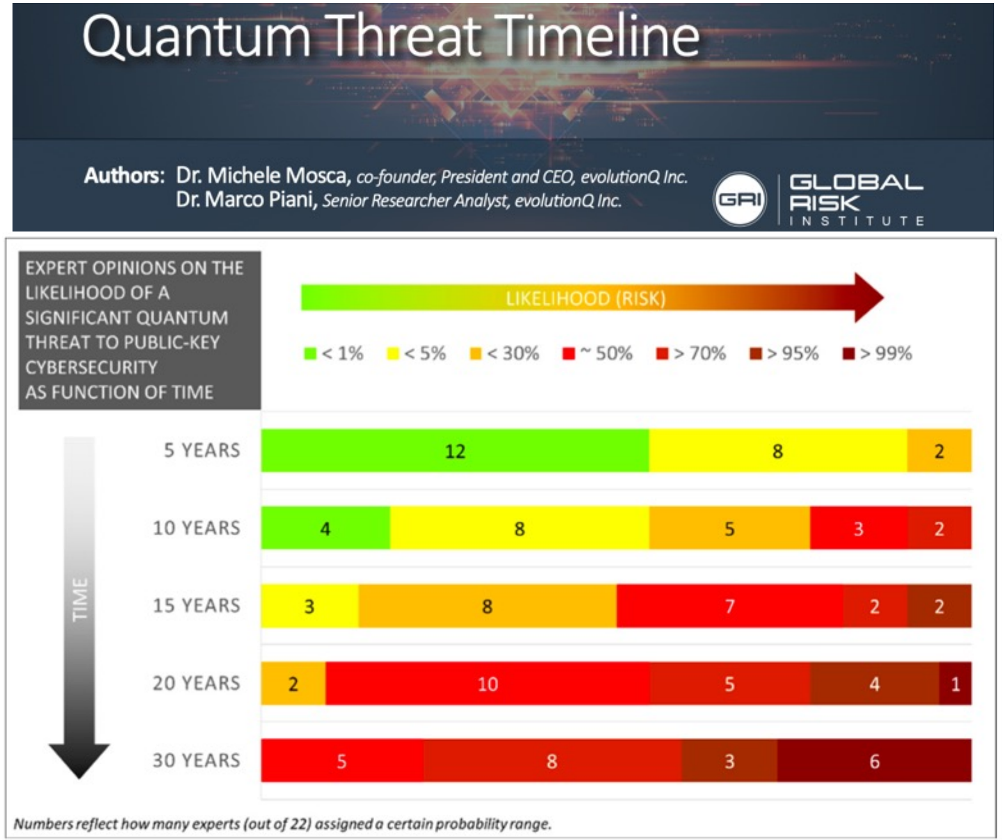
Need to migrate encryption to quantum-resistant algorithms

When should we start the process?

# 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, 2015


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

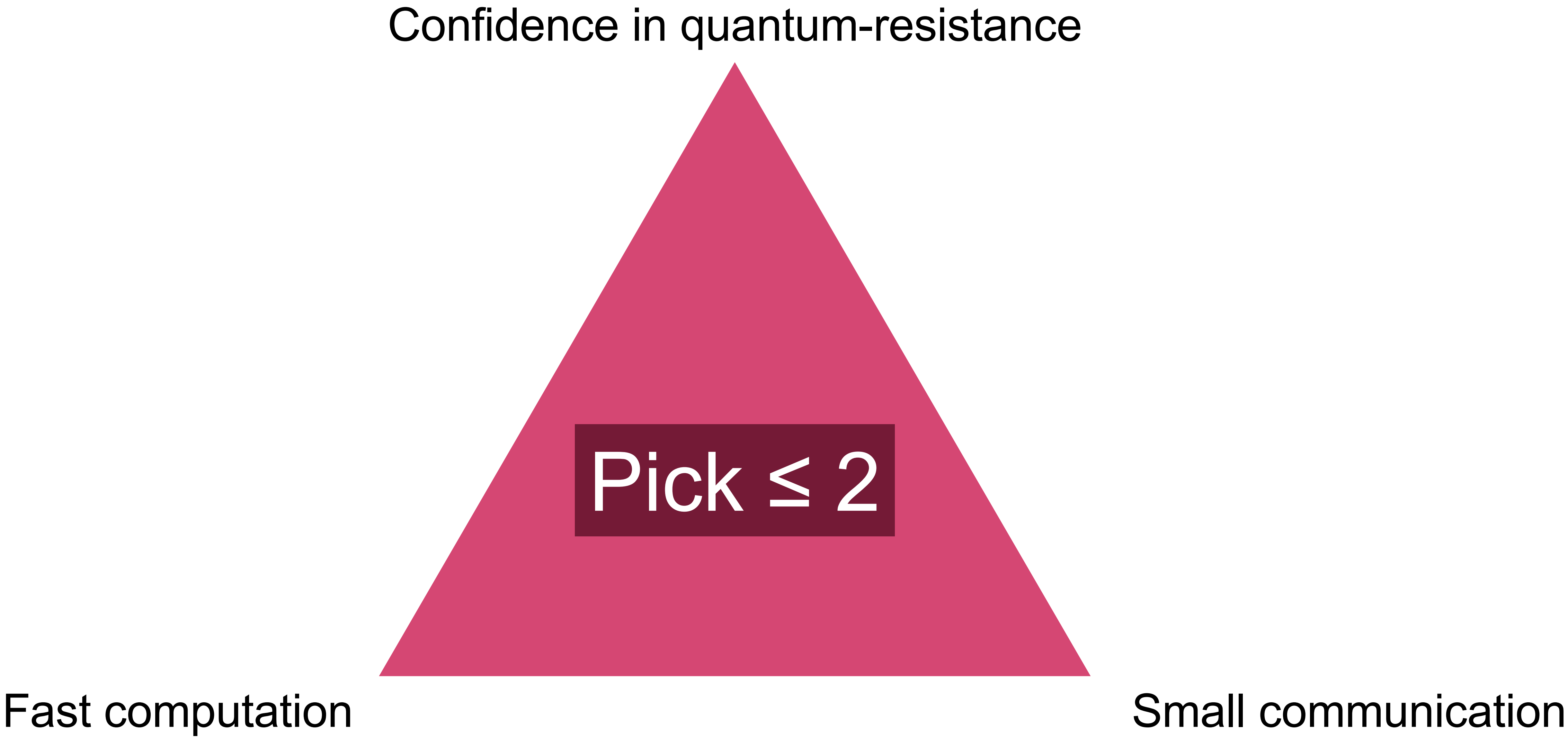
# Post-quantum cryptography

a.k.a. quantum-resistant algorithms

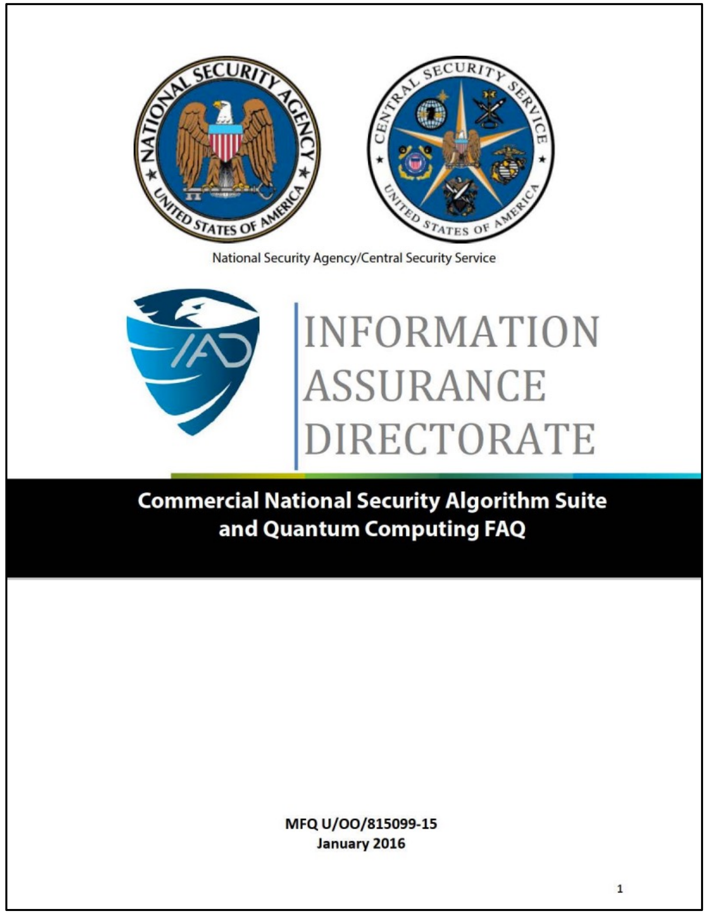
**Cryptography believed to be resistant to attacks by quantum computers**

Uses only classical (non-quantum) operations to implement

- Hash-based & symmetric
- Multivariate quadratic
- Code-based
- Lattice-based
- Elliptic curve isogenies


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

# Standardizing post-quantum cryptography

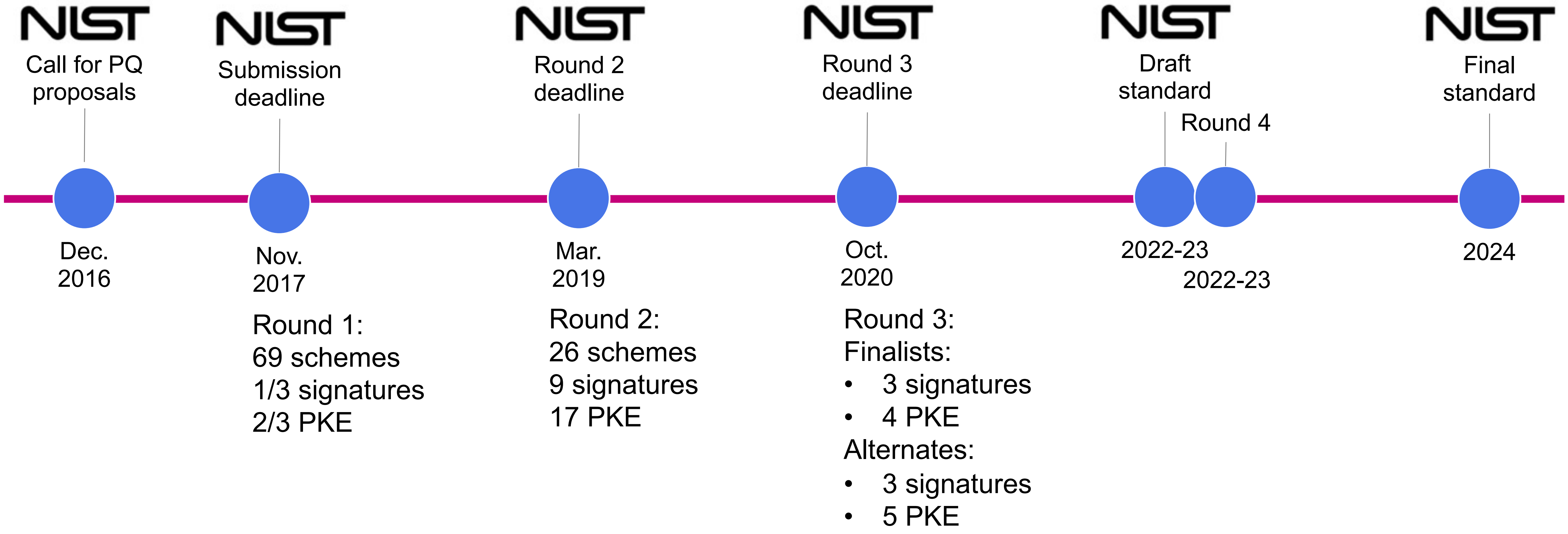



Aug. 2015 (Jan. 2016)

“IAD will initiate a transition to quantum resistant algorithms in the not too distant future.”

– NSA Information Assurance Directorate, Aug. 2015

# NIST Post-quantum Crypto Project timeline




http://www.nist.gov/pqcrypto

# Benchmarking post-quantum crypto in TLS

Christian Paquin, Douglas Stebila, Goutam Tamvada.
PQCrypto 2020.
https://eprint.iacr.org/2019/1447

# Goal

- Measure effect of **network latency** and **packet loss rate** on handshake completion time for post-quantum connections of various sizes

- Out of scope:
  - Effect of different CPU speeds from client or server
  - Effect of different post-quantum algorithms on server throughput

# Related work

- [BCNS15] and [BCD+16] measured the impact of their post-quantum key-exchange schemes on the performance of an Apache server running TLS 1.2
- [KS19] and [SKD20] measured the impact of post-quantum signatures in TLS 1.3 on handshake time (with various server distances), and handshake failure rate and throughput for a heavily loaded server

[BCNS15] Bos, Costello, Naehrig, Stebila. IEEE S&P 2015. https://eprint.iacr.org/2014/599
[BCD+16] Bos, Costello, Ducas, Mironov, Naehrig, Nikolaenko, Raghunathan, Stebila. ACM CCS 2016. https://eprint.iacr.org/2016/659
[KS19] Kampanakis, Sikeriis. https://eprint.iacr.org/2019/1276
[SKD20] Sikeridis, Kampanaokis, Devetsikiotis. NDSS 2020. https://eprint.iacr.org/2020/071

# Related work: Internet-wide experiments

**2016**

Google, with NewHope in TLS 1.2

→

**2018**

Google, with “dummy extensions”

→

**2019**

Google and Cloudflare, with SIKE and NTRU-HRSS in TLS 1.3

Langley, 2016. https://www.imperialviolet.org/2016/11/28/cecpq1.html
Langley, 2018. https://www.imperialviolet.org/2018/12/12/cecpq2.html
Sullivan, Kwiatkowski, Langley, Levin, Mislove, Valenta. NIST 2nd PQC Standardization Conference 2019. https://csrc.nist.gov/Presentations/2019/measuring-tls-key-exchange-with-post-quantum-kem

# What if you don't have billions of clients and millions of servers?

(Inspired by NetMirage and Mininet)

Emulate the network!

+ more control over experiment parameters

+ easier to isolate effects of network characteristics

– loss in realism

# Network emulation in Linux

- Kernel can create **network namespaces**: Independent copies of the kernel's network stack
- **Virtual ethernet devices** can be created to connect the two namespaces
- **netem (network emulation)** kernel module
  - Can instruct kernel to apply a specified delay to packets
  - Can instruct kernel to drop packets with a specified probability

# Open Quantum Safe Project

Use in applications

Apache httpd | nginx | curl, links | Open VPN | Chromium

Integration into forks of widely used open-source projects

**OpenSSL**
**S/MIME, TLS 1.3, X.509**
**OpenSSL 3 provider**

**BoringSSL**

**Open SSH**

**Language SDKs**
**C#, C++, Go, Java, Python, Rust**

C language library, common API
- x86/x64 (Linux, Mac, Windows)
- ARM (Android, Linux)

**liboqs**

key exchange / KEMs

signatures

isogenies | code-based | lattice-based | multi-variate polynomial | hash-based / symmetric

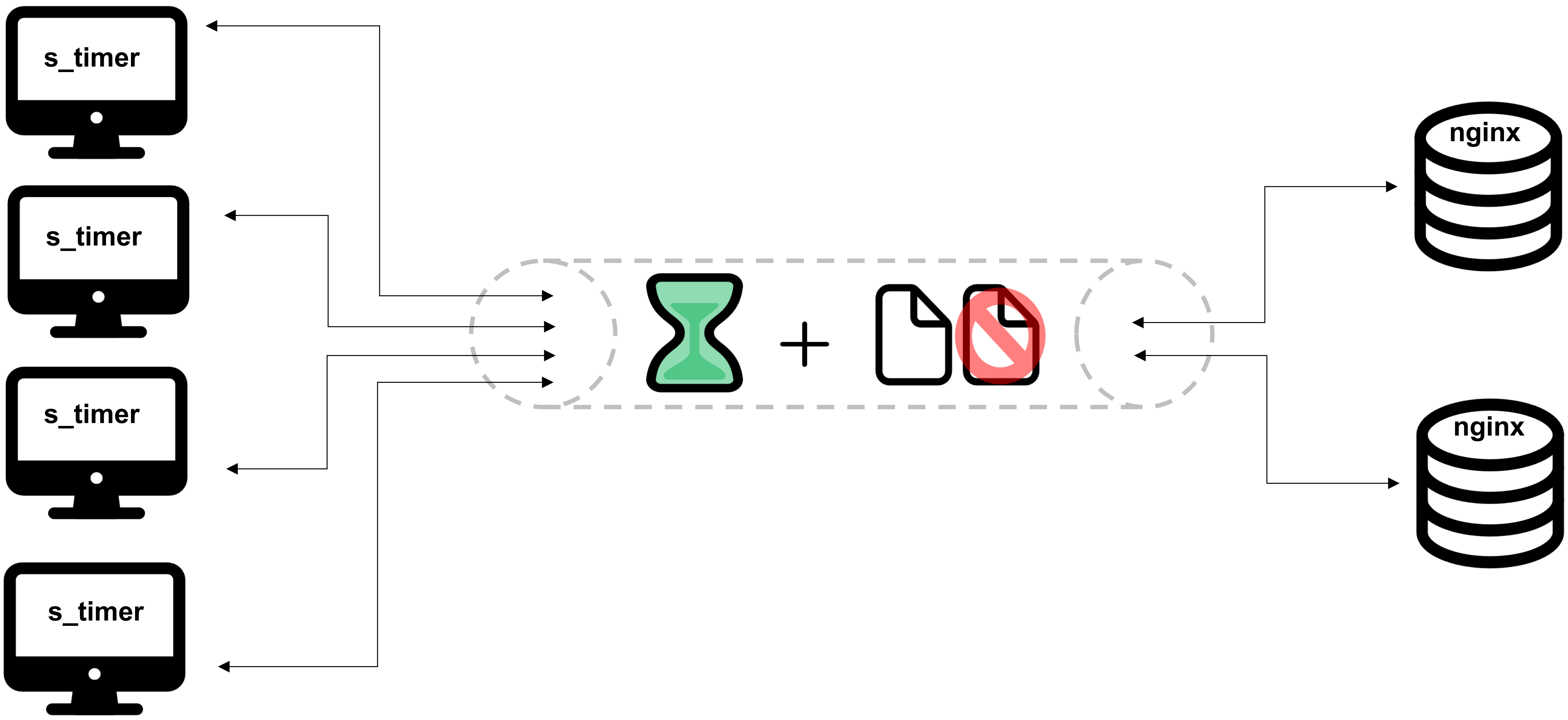
Industry partners:
- Amazon Web Services
- evolutionQ
- IBM Research
- Microsoft Research

Additional contributors:
- Cisco
- Senetas
- PQClean project
- Individuals

Financial support:
- AWS
- Canadian Centre for Cyber Security
- NSERC
- Unitary Fund

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

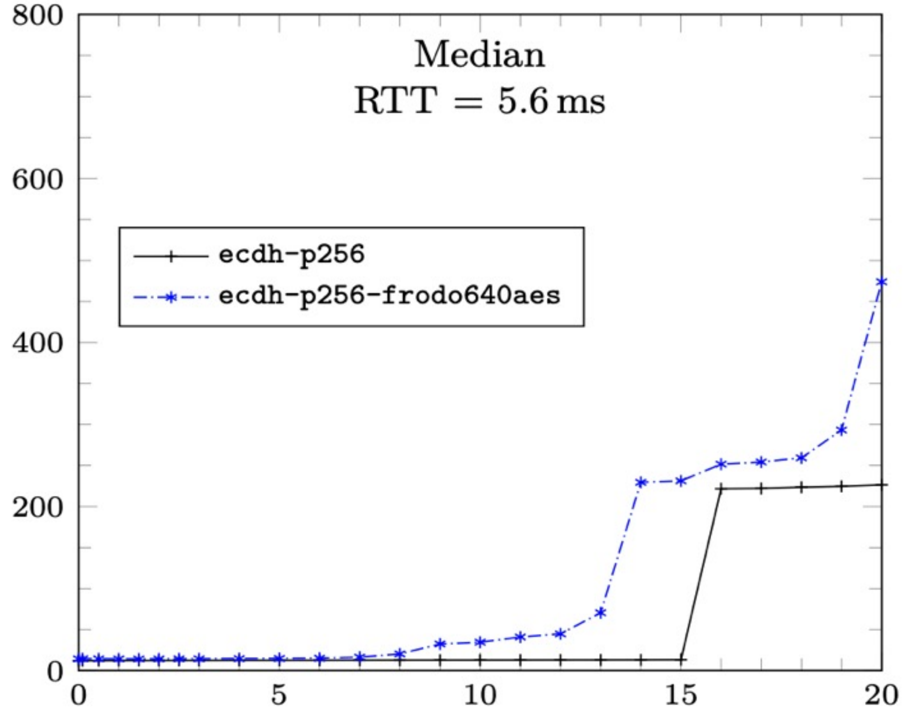
# Network emulation experiment (contd.)




Icons from https://ionicons.com/

# Key exchange in TLS 1.3

## median

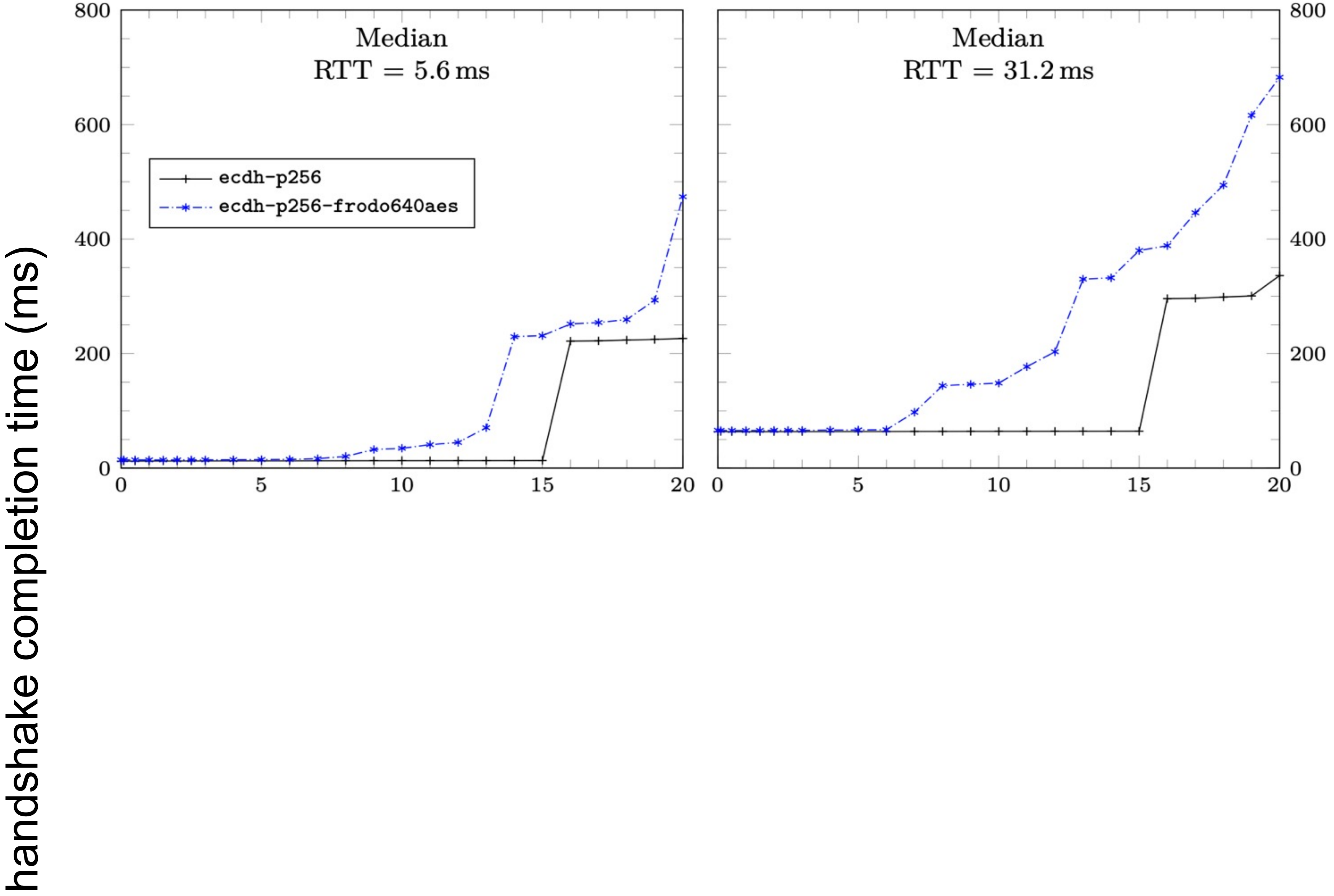



handshake completion time (ms)

packet loss rate %

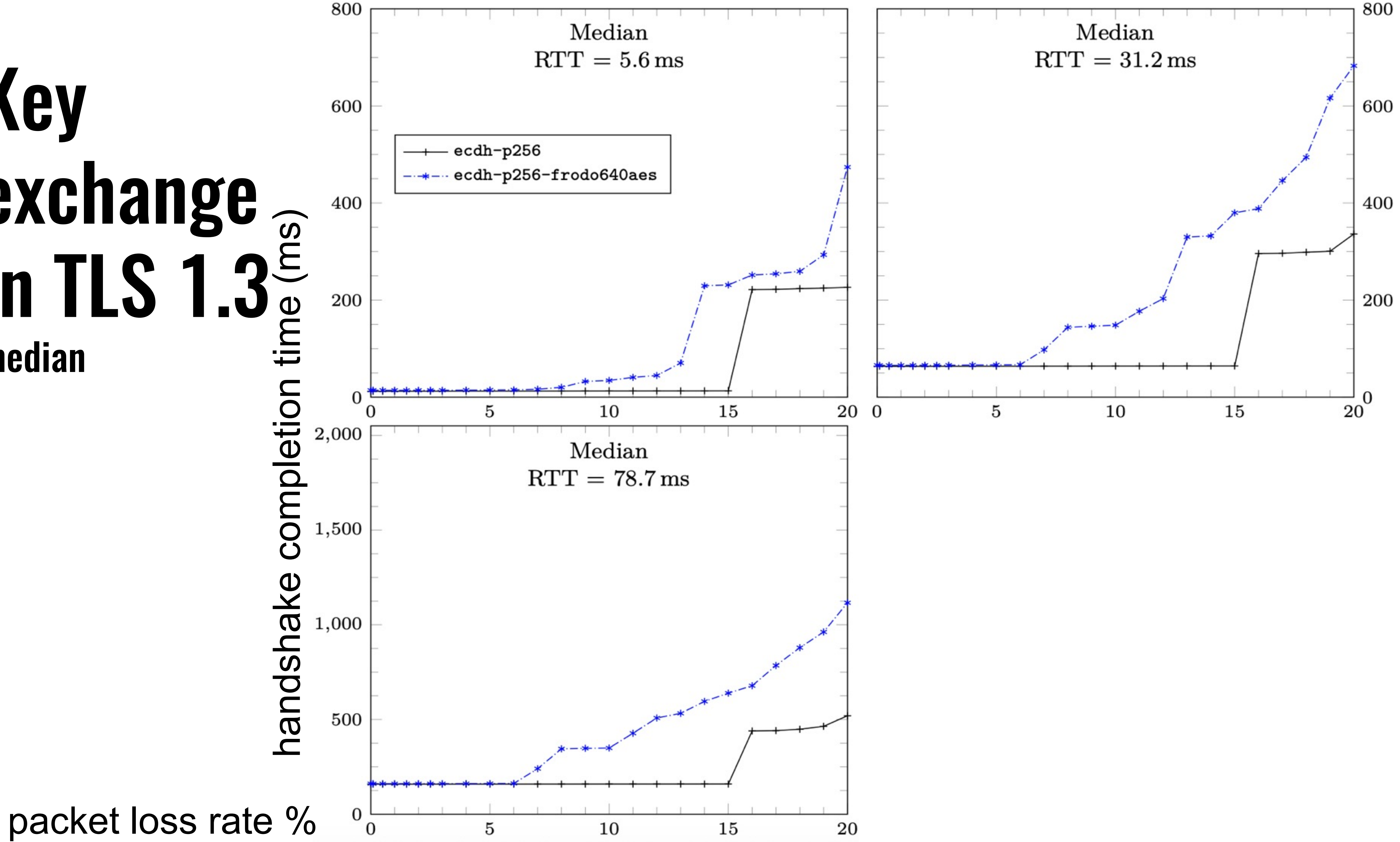
# Key exchange in TLS 1.3

**median**



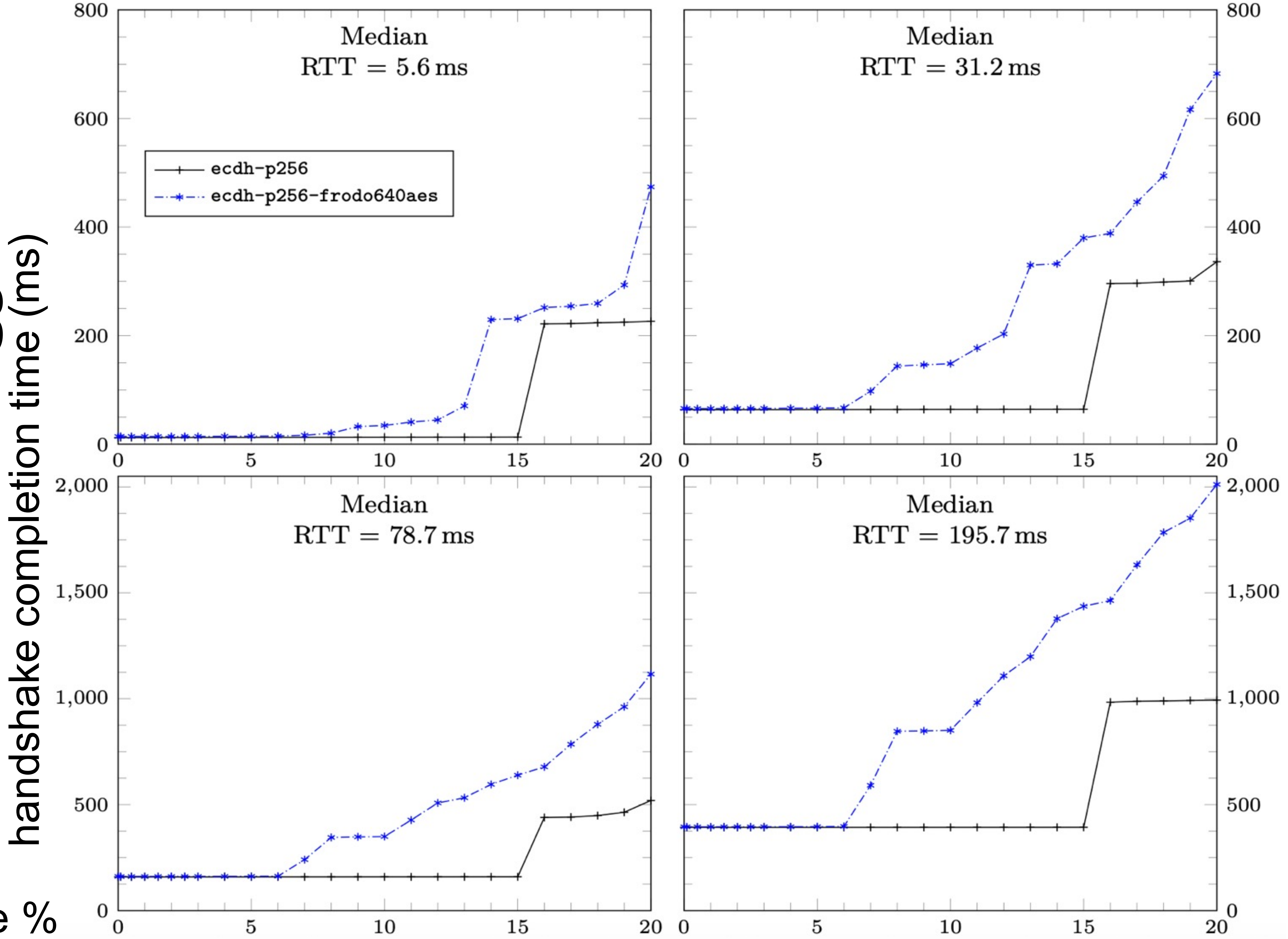

packet loss rate %

# Key exchange in TLS 1.3
## median



# Key exchange in TLS 1.3

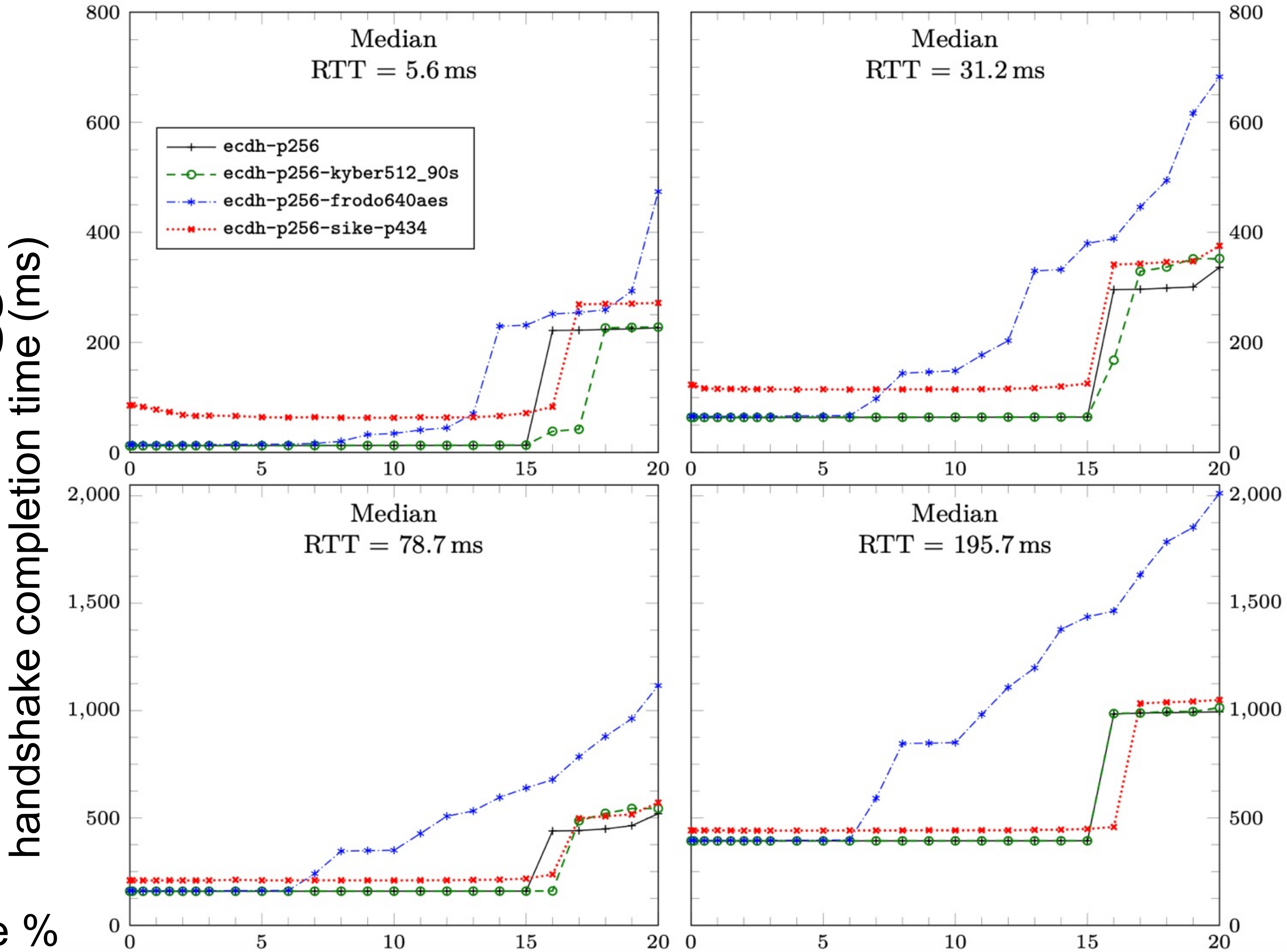
**median**




packet loss rate %

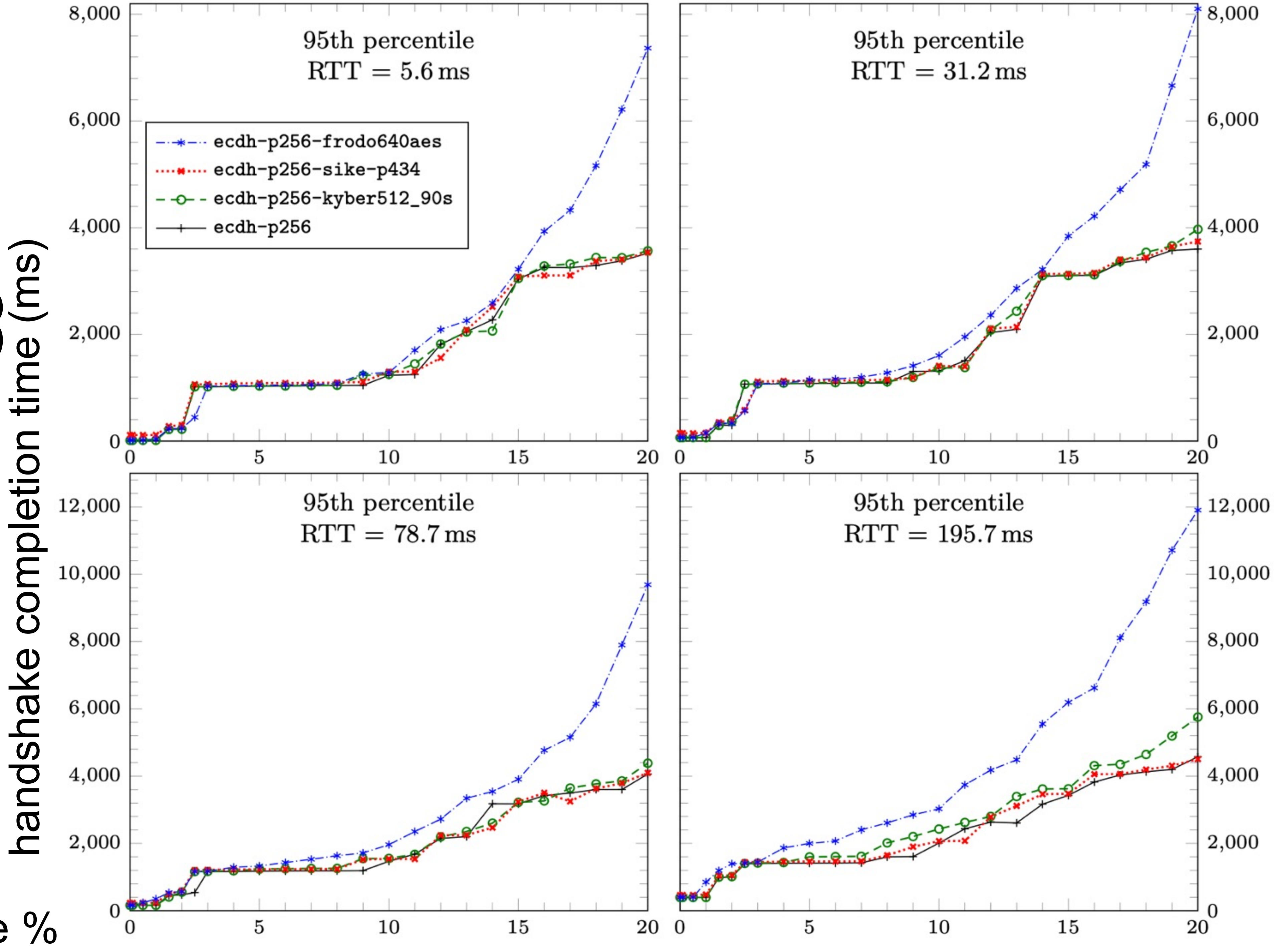
# Key exchange in TLS 1.3

**median**



# Key exchange in TLS 1.3

## 95th percentile



# Conclusions

- On **fast, reliable network links**, the cost of public key cryptography dominates the median TLS establishment time, but does not substantially affect the 95th percentile establishment time
- On **unreliable network links** (packet loss rates >= 3%), communication sizes come to govern handshake completion time
- As application data sizes grow, the relative cost of TLS handshake establishment diminishes compared to application data transmission

# Hybrid key exchange in TLS 1.3

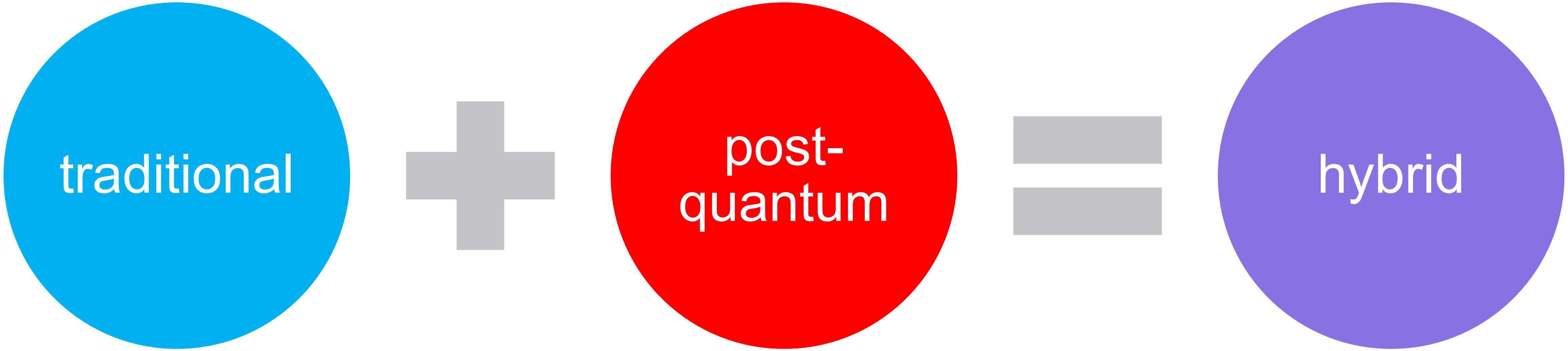
## draft-ietf-tls-hybrid-design-03

Douglas Stebila, Scott Fluhrer, Shay Gueron

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

# Cautious "hybrid" approach

- Some proposed post-quantum solutions could be broken
- **Hybrid approach**: use traditional and post-quantum simultaneously to reduce risk during transition



# Hybrid approach

- **Permit simultaneous use of traditional and post-quantum key exchange**

- Enable early adopters to get post-quantum security without discarding security of existing algorithms
- Why do this?
  - Uncertainty re: newer cryptographic assumptions
  - Temporary need to keep traditional algorithms for e.g. FIPS certification

# 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

* Some people use the word “composite” instead of “hybrid”.

# Mechanism

**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
- Extension for representing algorithm options and constraints

## Key shares

- Separately list key shares for each algorithm
- Use extensions for extra key shares

## Shared secret

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

See Appendix A of draft for related work and Appendix B for detailed discussion of other design options.

# 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

# Securely combining keying material

Is it okay to use concatenation?

$ss = k_1 \,||\, k_2$

$ss = H(k_1 \,||\, k_2)$

- Aviram et al: If H is not collision resistant, then concatenating secrets may be dangerous.
  - Attack if $k_1$ is adversary-controlled and variable length, like APOP or CRIME attacks.
  - Applies to other parts of the TLS 1.3 key schedule.
  - Currently discussing impact and mitigation.

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

# New 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

# 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** |
|---|---|---|
| $(pk_A, sk_A) \leftarrow \mathrm{SIG.KeyGen}()$ | | $(pk_B, sk_B) \leftarrow \mathrm{SIG.KeyGen}()$ |
| obtain $pk_B$ | | obtain $pk_A$ |
| $x \leftarrow_{\$} \{0, \ldots, q-1\}$ | | |
| $X \leftarrow g^x$ | $X$ $\longrightarrow$ | |
| | | $y \leftarrow_{\$} \{0, \ldots, q-1\}$ |
| | | $Y \leftarrow g^y$ |
| | | $\sigma_B \leftarrow \mathrm{SIG.Sign}(sk_B, A\|B\|X\|Y)$ |
| | $\longleftarrow$ $Y, \sigma_B$ | |
| $\sigma_A \leftarrow \mathrm{SIG.Sign}(sk_A, A\|B\|X\|Y)$ | $\sigma_A$ $\longrightarrow$ | |
| $k \leftarrow H(sid, Y^x)$ | | $k \leftarrow H(sid, X^y)$ |
| | application data $\Longleftrightarrow$ using authenticated encryption | |

# Implicitly authenticated key exchange: Double-DH

| Alice | | Bob |
|---|---|---|
| $sk_A \leftarrow_\$ \{0,\ldots,q-1\}$ | | $sk_B \leftarrow_\$ \{0,\ldots,q-1\}$ |
| $pk_A \leftarrow g^{sk_A}$ | | $pk_B \leftarrow g^{sk_B}$ |
| obtain $pk_B$ | | obtain $pk_A$ |
| $x \leftarrow_\$ \{0,\ldots,q-1\}$ | | $y \leftarrow_\$ \{0,\ldots,q-1\}$ |
| $X \leftarrow g^x$ | $X$ $\longrightarrow$ | $Y \leftarrow g^y$ |
| | $\longleftarrow$ $Y$ | |
| $k \leftarrow H(sid, pk_B^{sk_A} \| Y^x)$ | | $k \leftarrow H(sid, pk_A^{sk_B} \| X^y)$ |
| | 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) |
|---|---|---|---|
| RSA-2048 | Factoring | 272 | 256 |
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| **XMSS** | **Hash-based** | **32** | **979** |
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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

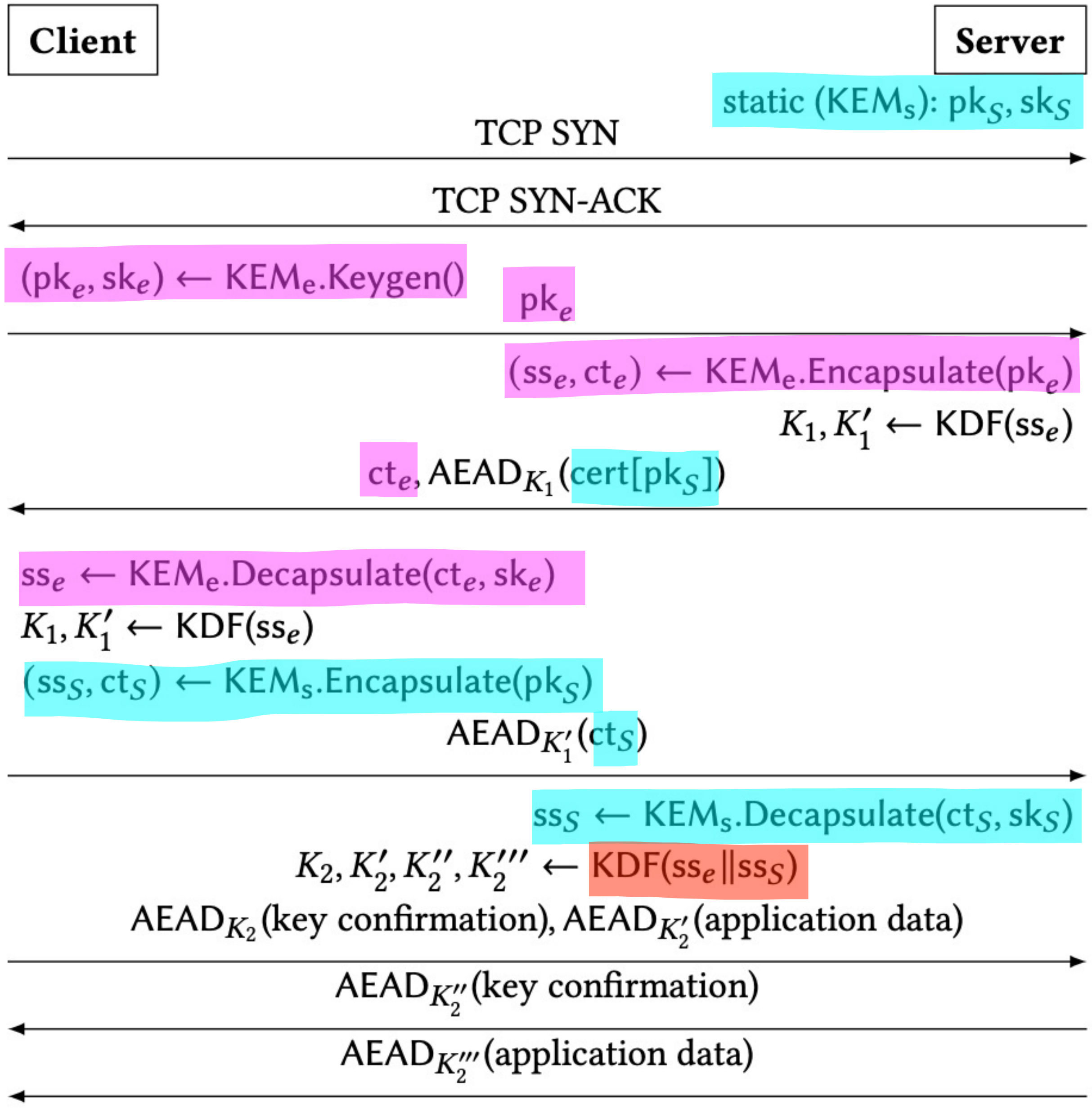
- RSA key transport in TLS ≤ 1.2
  - Lacks forward secrecy
- Signal, Noise, Wireguard
  - DH-based
  - Different protocol flows
- OPTLS
  - DH-based
  - Requires a non-interactive key exchange (NIKE)

# “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**

- 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

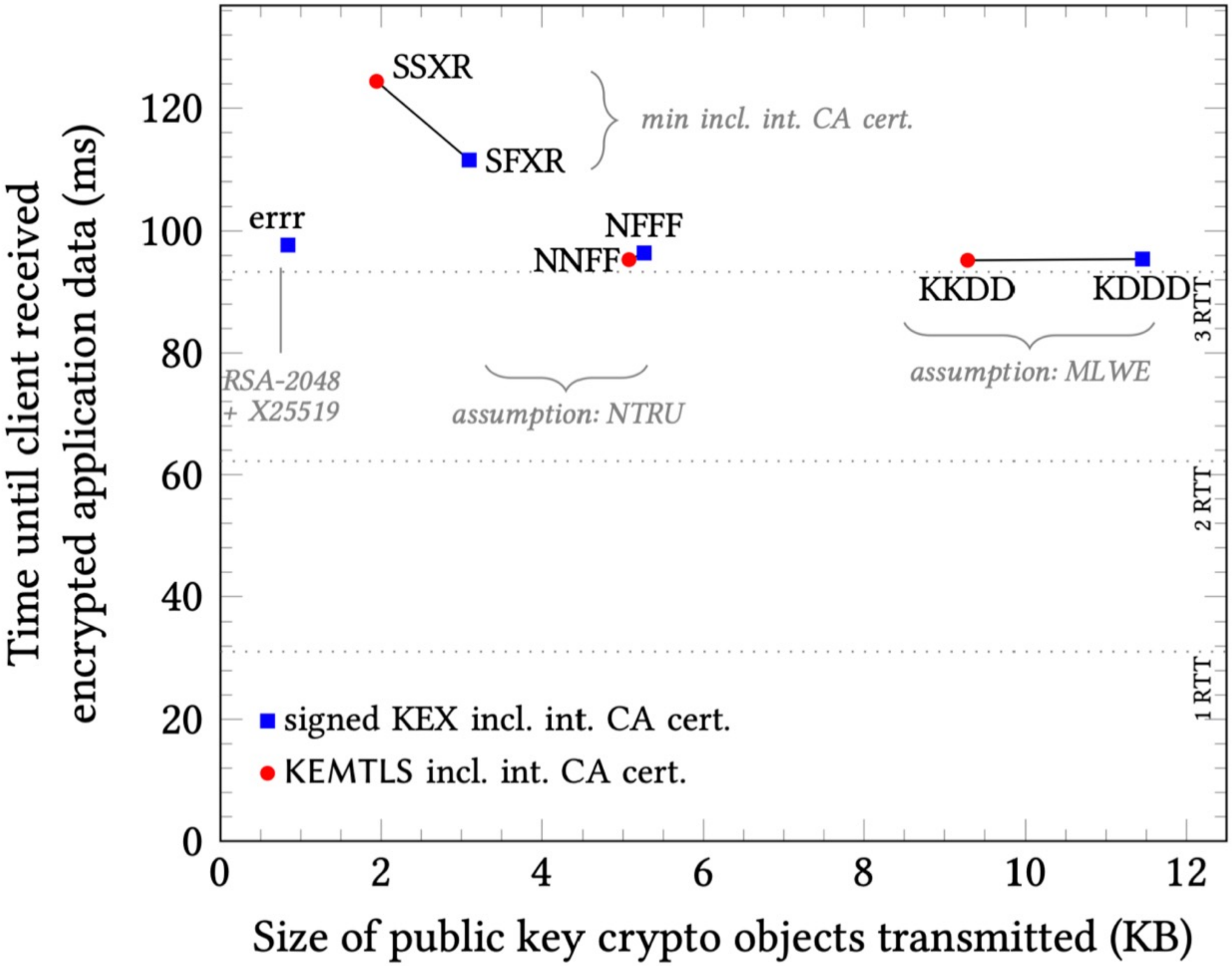
# 4 scenarios

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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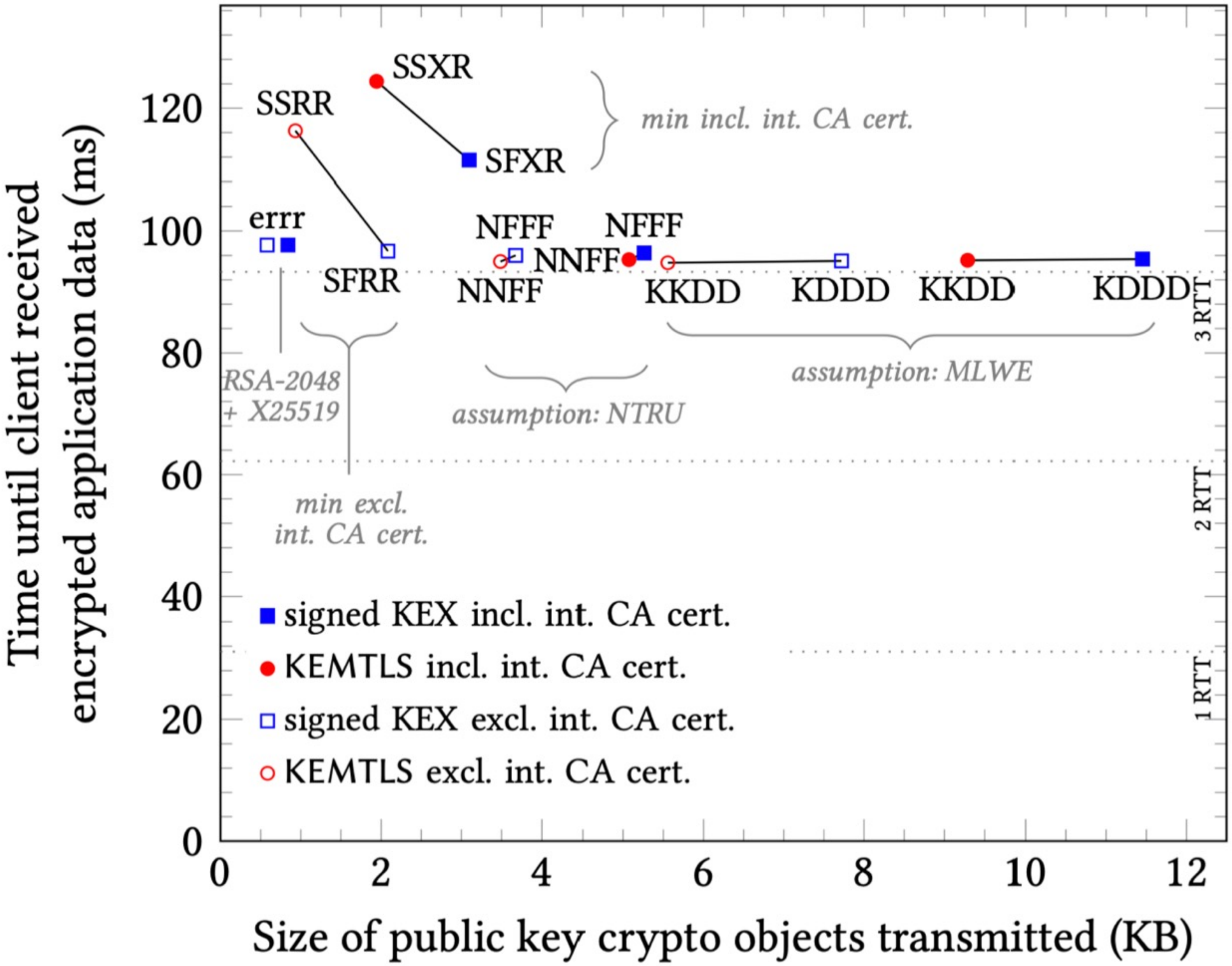
rSA-2048,
SIKE,
XMSS'




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

# 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

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

- 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

TLS 1.3 already supports pre-shared symmetric keys

- Harder(?) key management problem
- Different compromise model

# KEMTLS-PDK

- Alternate KEMTLS protocol flow when server certificates are known in advance

https://thomwiggers.nl/publication/kemtlspdk/

# KEMTLS-PDK benefits

- 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

| | 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 | 4 | 3 | 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 |

# 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
  - e.g. HTTP3 SETTINGS frame not server authenticated
- PKI involving KEM public keys
- Long tail of implementations
- …

# 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 security

Douglas Stebila
UNIVERSITY OF WATERLOO

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

## Benchmarking and 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

Working towards standardization

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

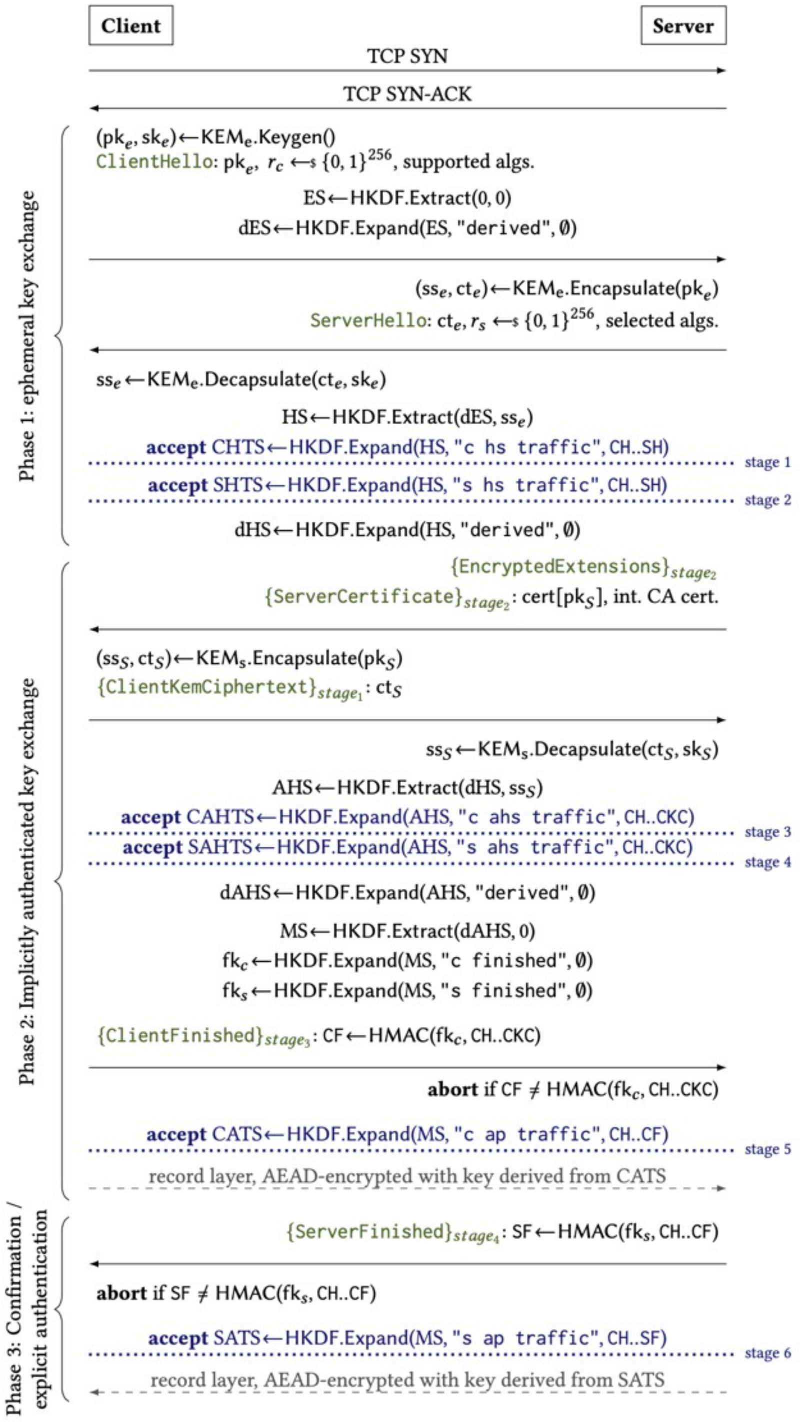
## KEMTLS

Implicitly authenticated TLS without handshake signatures using KEMs

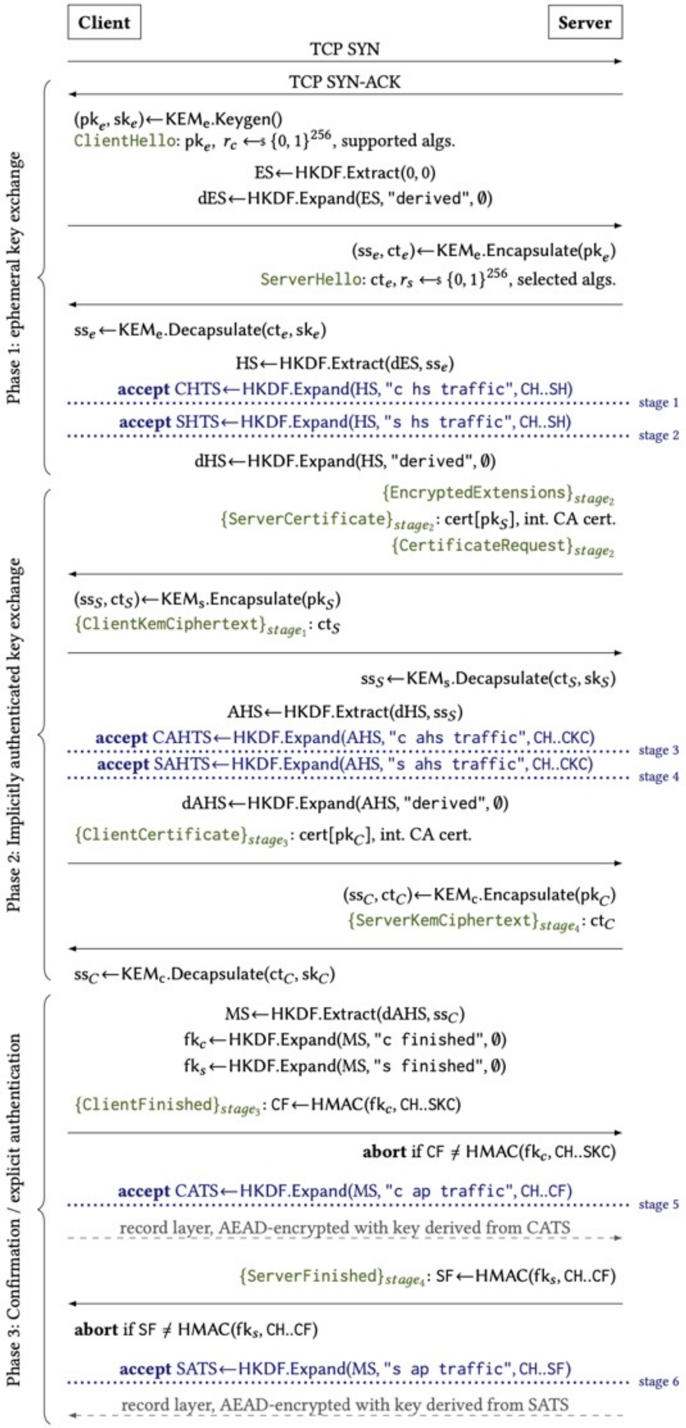
- Saves bytes on the wire and server CPU cycles
- Variants for client authentication and pre-distributed public keys
- Lots of work to make viable in TLS ecosystem, including certificates

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

# 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

| | | Abbrv. | KEX (pk+ct) | Excluding intermediate CA certificate<br>HS auth (ct/sig) | Leaf crt. subject (pk) | Leaf crt. (signature) | Sum excl. int. CA cert. | Including intermediate CA certificate<br>Int. CA crt. subject (pk) | Int. CA crt. (signature) | Sum incl. int. CA crt. | Root CA (pk) | Sum TCP payloads of TLS HS (incl. int. CA crt.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **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 |
| TLS 1.3 (Signed KEX) | **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 |
| TLS 1.3 (Signed KEX) | **Min. excl. int. CA cert.** | SFRR | SIKE 433 | Falcon 690 | Falcon 897 | Rainbow 66 | **2086** | Rainbow 60192 | Rainbow 66 | **62344** | Rainbow 60192 | 64693 |
| TLS 1.3 (Signed KEX) | **Assumption: MLWE+MSIS** | KDDD | Kyber 1568 | Dilithium 2420 | Dilithium 1312 | Dilithium 2420 | **7720** | Dilithium 1312 | Dilithium 2420 | **11452** | Dilithium 1312 | 12639 |
| TLS 1.3 (Signed KEX) | **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 |
| KEMTLS | **Min. excl. int. CA cert.** | SSRR | SIKE 433 | SIKE 236 | SIKE 197 | Rainbow 66 | **932** | Rainbow 60192 | Rainbow 66 | **61190** | Rainbow 60192 | 63568 |
| KEMTLS | **Assumption: MLWE+MSIS** | KKDD | Kyber 1568 | Kyber 768 | Kyber 800 | Dilithium 2420 | **5556** | Dilithium 1312 | Dilithium 2420 | **9288** | Dilithium 1312 | 10471 |
| KEMTLS | **Assumption: NTRU** | NNFF | NTRU 1398 | NTRU 699 | NTRU 699 | Falcon 690 | **3486** | Falcon 897 | Falcon 690 | **5073** | Falcon 897 | 6359 |

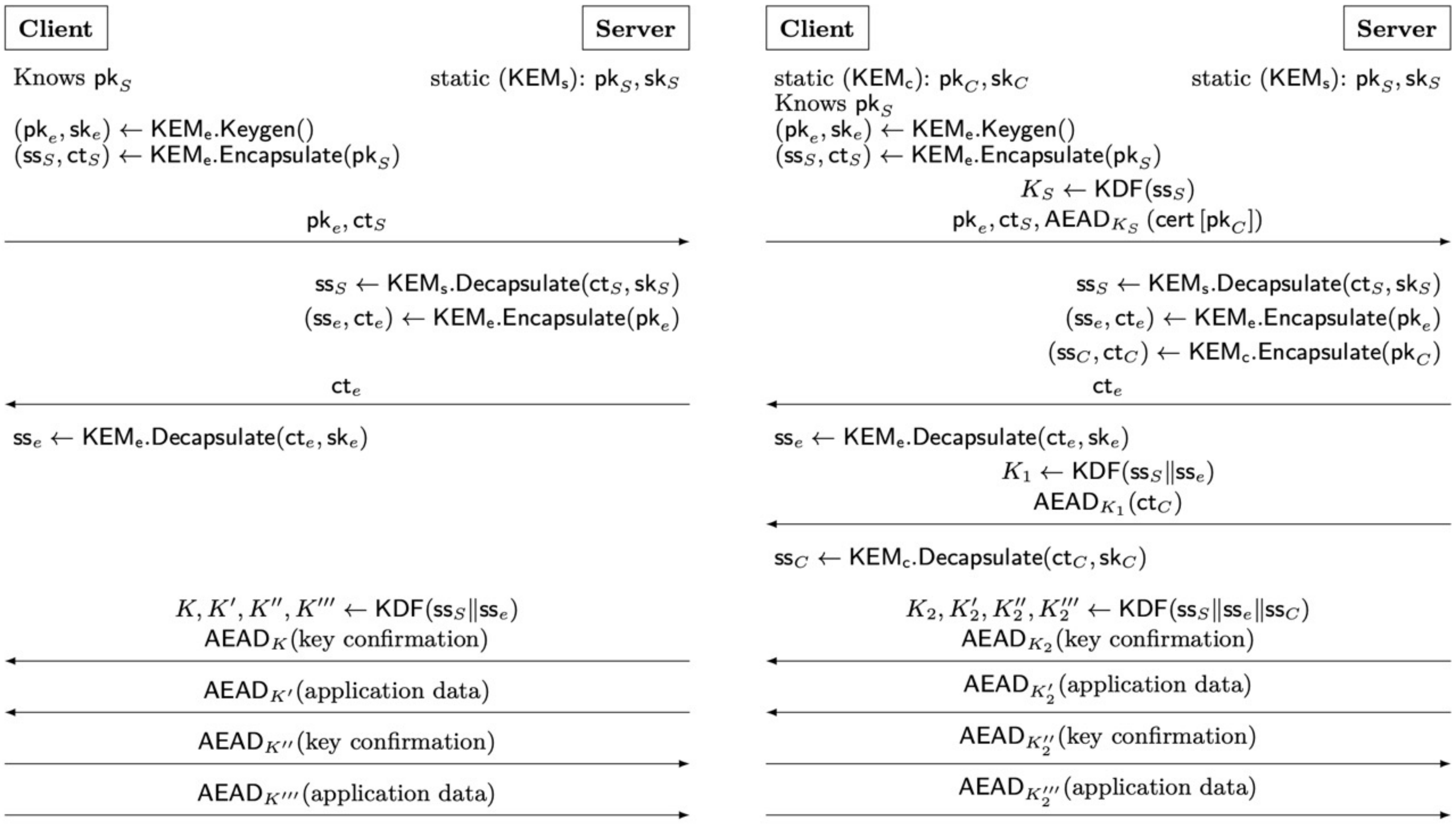
# TLS 1.3 and KEMTLS crypto & handshake time

| | | 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.

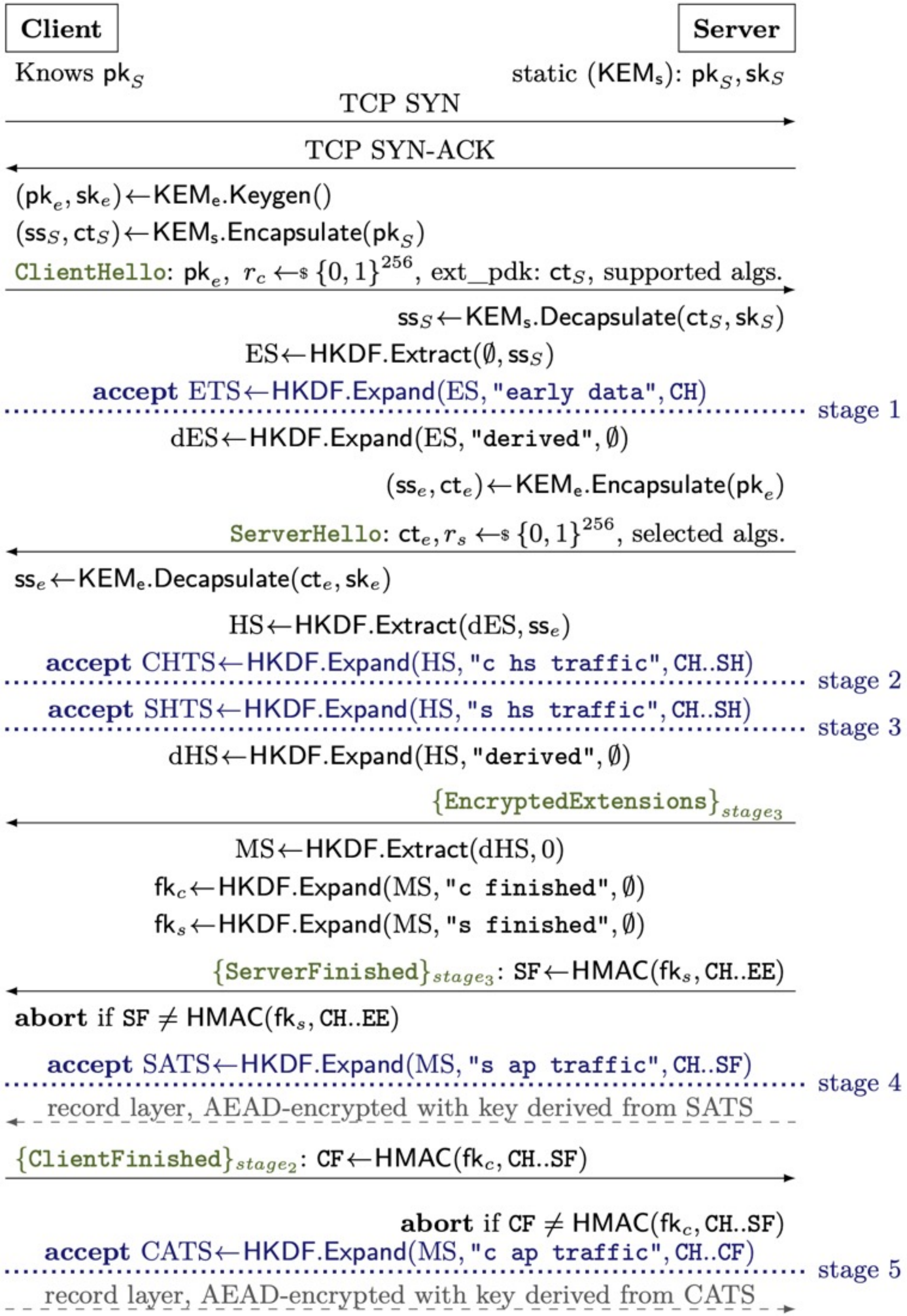
# KEMTLS-PDK overview




(a) Unilaterally authenticated

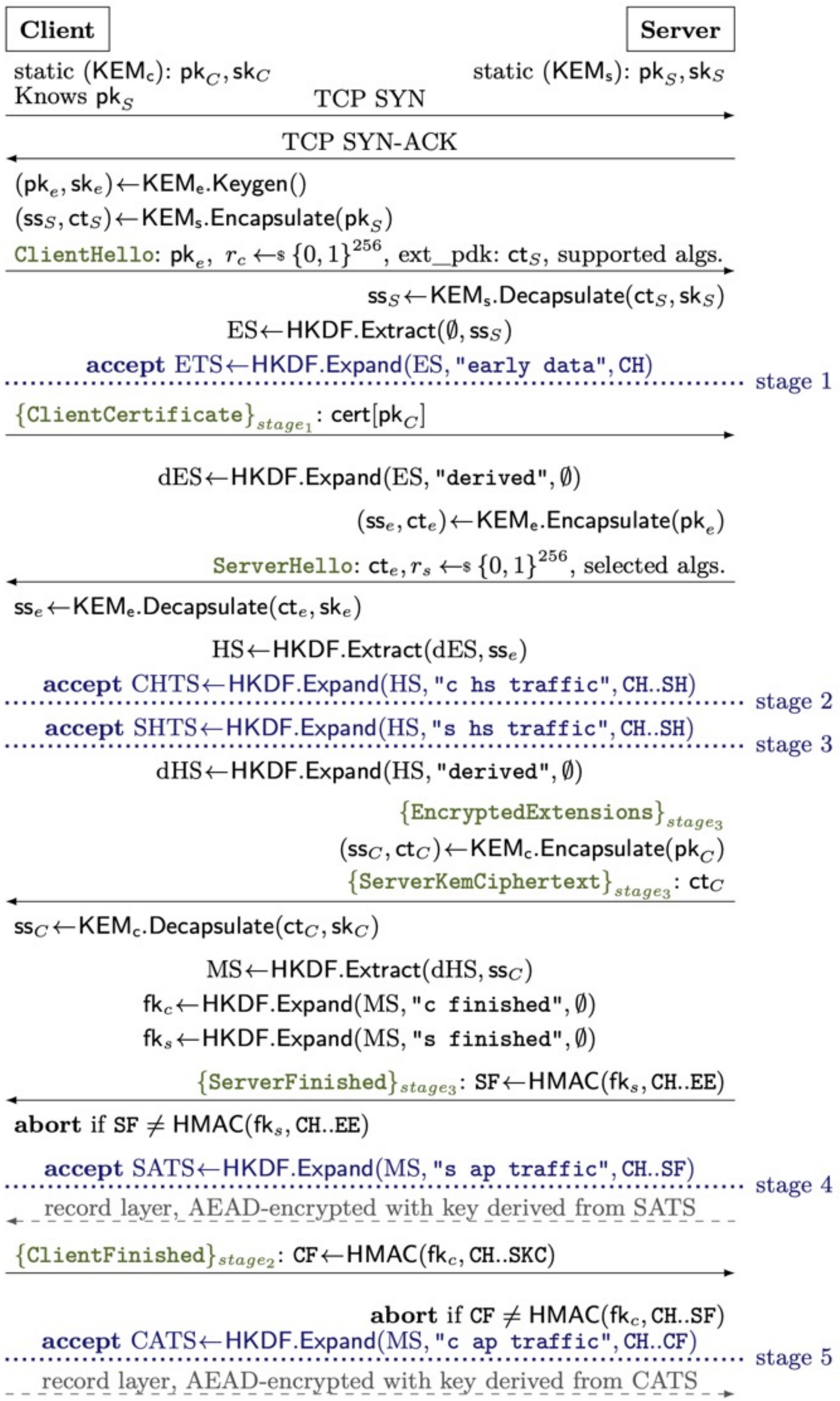
(b) With proactive client authentication

# KEMTLS-PDK



Client
Server
Knows pk_S
static (KEMs): pk_S, sk_S
TCP SYN
TCP SYN-ACK
(pk_e, sk_e) ← KEMe.Keygen()
(ss_S, ct_S) ← KEMs.Encapsulate(pk_S)
ClientHello: pk_e, r_c ←$ {0,1}^256, ext_pdk: ct_S, supported algs.
ss_S ← KEMs.Decapsulate(ct_S, sk_S)
ES ← HKDF.Extract(∅, ss_S)
accept ETS ← HKDF.Expand(ES, "early data", CH)
stage 1
dES ← HKDF.Expand(ES, "derived", ∅)
(ss_e, ct_e) ← KEMe.Encapsulate(pk_e)
ServerHello: ct_e, r_s ←$ {0,1}^256, selected algs.
ss_e ← KEMe.Decapsulate(ct_e, sk_e)
HS ← HKDF.Extract(dES, ss_e)
accept CHTS ← HKDF.Expand(HS, "c hs traffic", CH..SH)
stage 2
accept SHTS ← HKDF.Expand(HS, "s hs traffic", CH..SH)
stage 3
dHS ← HKDF.Expand(HS, "derived", ∅)
{EncryptedExtensions}stage3
MS ← HKDF.Extract(dHS, 0)
fk_c ← HKDF.Expand(MS, "c finished", ∅)
fk_s ← HKDF.Expand(MS, "s finished", ∅)
{ServerFinished}stage3: SF ← HMAC(fk_s, CH..EE)
abort if SF ≠ HMAC(fk_s, CH..EE)
accept SATS ← HKDF.Expand(MS, "s ap traffic", CH..SF)
stage 4
record layer, AEAD-encrypted with key derived from SATS
{ClientFinished}stage2: CF ← HMAC(fk_c, CH..SF)
abort if CF ≠ HMAC(fk_c, CH..SF)
accept CATS ← HKDF.Expand(MS, "c ap traffic", CH..CF)
stage 5
record layer, AEAD-encrypted with key derived from CATS

# KEMTLS-PDK with proactive client authentication



# 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 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 | 75.4 | **116.1** | 116.1 | 408.6 | **616.3** | 616.2 |
| KEMTLS | MLWE/MSIS | 63.2 | **94.8** | 94.7 | 397.4 | **594.6** | 594.5 |
| KEMTLS | 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 |
| Cached TLS | Minimum | 70.1 | **101.3** | 70.0 | 402.3 | **598.5** | 402.2 |
| Cached TLS | MLWE/MSIS | 63.9 | **95.1** | 63.8 | 397.2 | **593.4** | 397.1 |
| Cached TLS | 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 |
| PDK | Kyber | 63.1 | **94.3** | 63.0 | 395.3 | **591.4** | 395.2 |
| PDK | NTRU | 63.1 | **94.3** | 63.0 | 395.3 | **591.5** | 395.2 |
| PDK | 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 0.7.0 released August 2021
- Includes all Round 3 finalists and alternate candidates
  - (except GeMSS)
  - Some implementations still Round 2 versions

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

- 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

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

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