Real-world post-quantum TLS in Wireshark

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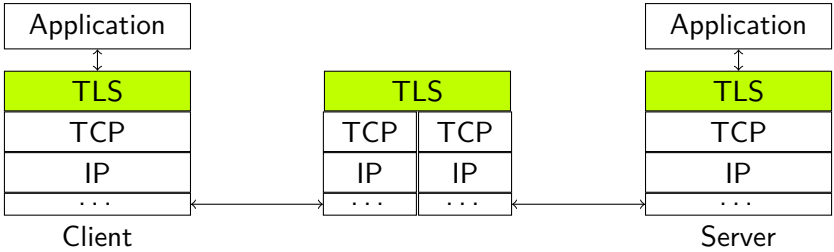
About me

- Wireshark contributor since 2013, core developer since 2015.
- Areas of interest: TLS, QUIC, HTTP/3, Lua, security, ...
- Cloudflare Research team. Recently worked on rolling out post-quantum TLS.

- Standard for securing network traffic. Web (HTTP), e-mail, databases, etc.
- Provides secure communication channel between two endpoints (client and server).
- Network protocol with two components:
  - Handshake Protocol: exchange capabilities, establish trust and establish keys.
  - Record Protocol: carries messages and protects application data fragments.



- Powerful quantum computers are expected in 15 to 40 years.[1]
- Essentially all Internet traffic today can be decrypted by these.
- Post-quantum (PQ) cryptography was designed to be secure against this threat.
- In active development: US National Institute of Standards and Technology (NIST) is almost done standardizing the initial post-quantum public-key algorithms.

[1] `https://blog.cloudflare.com/post-quantum-for-all/`

- Text file with unique per-session secrets[2].
- TLS 1.2 format: `CLIENT_RANDOM` *<Client Hello Random> <master secret>*
- TLS 1.3 requires four different secrets (handshake and traffic secrets).

```
CLIENT_RANDOM 607AAA3D657D8A08F1073AE75B62CD284C87BB5504D275631CA86533707FB080 B27567070A3832CA2C072D1D0905647EF364C1E017A33001ED0BB2E
CLIENT_HANDSHAKE_TRAFFIC_SECRET e27a03ae85ae8035b331a1af6089dd1e2f300cce131b03fdb9f07a25f1a10876 8ac2e7e210e30e8f660048e20d45209935d6a
SERVER_HANDSHAKE_TRAFFIC_SECRET e27a03ae85ae8035b331a1af6089dd1e2f300cce131b03fdb9f07a25f1a10876 21c21f13865944c2c411ed1a7271809834dbe
CLIENT_TRAFFIC_SECRET_0 e27a03ae85ae8035b331a1af6089dd1e2f300cce131b03fdb9f07a25f1a10876 0de57183beff9a8c43994f517fba1d79ca374bff53b2a
SERVER_TRAFFIC_SECRET_0 e27a03ae85ae8035b331a1af6089dd1e2f300cce131b03fdb9f07a25f1a10876 f26e64d69b8095bbcdcbd04d48f2f9d96aedc1abc6463
```

- Import these secrets to Wireshark: *Edit* → *Preferences*, *Protocols* → *TLS*, *(Pre)-Master-Secret log filename*. Or right-click packet, *Protocol Preferences*.
- Ensure *Protocol Preferences* → TCP → *Reassemble out-of-order segments* is set!
- `tshark -otls.keylog_file:keys.txt -r some.pcapng -otcp.reassemble_out_of_order:TRUE`

[2]File format at `https://www.ietf.org/archive/id/draft-ietf-tls-keylogfile-02.html`

- Set environment variable `SSLKEYLOGFILE` **before** starting Firefox or Chrome. Programs will append secrets to a file at this location.
- Start capture **before** running the application to capture the whole TLS handshake.
- Firefox on Windows, create `start-fx.cmd` file, without quotes in the `set` line:

```
set SSLKEYLOGFILE=C:\Users\User\Desktop\keys.txt
start firefox
```

- Chrome on Windows, create a shortcut with:

```
chrome --ssl-key-log-file="C:\Users\User\Desktop\keys.txt"
```

- One-liner for Linux and macOS, start Firefox or Chromium with a new profile:

```
SSLKEYLOGFILE="$PWD/keys.txt" firefox -no-remote -profile /tmp/ff
SSLKEYLOGFILE="$PWD/keys.txt" chromium --user-data-dir=/tmp/cr
```

- For macOS:

```
export SSLKEYLOGFILE="$PWD/keys.txt";
open -na Google\ Chrome --args --user-data-dir=/tmp/cr
```

- curl 7.58.0 built with OpenSSL supports it too. (Not on macOS.)

- TLS decryption requires pairing capture files with key log files. This makes switching between different files and file distribution more difficult.
- Solution: embed key log file in a **pcapng** file. Decryption Secrets Block (DSB).
- `editcap --inject-secrets tls,keys.txt in.pcap out-dsb.pcapng`
- Replace secrets: `editcap --discard-all-secrets --inject-secrets ...`
- inject-tls-secrets.py: script to embed a subset of TLS secrets in a pcapng file.[3] Example: given keys.txt and some.pcap, create some-dsb.pcapng: `./inject-tls-secrets.py keys.txt some.pcap`
- Since Wireshark 4.2: *Edit* → *Inject TLS Secrets*.

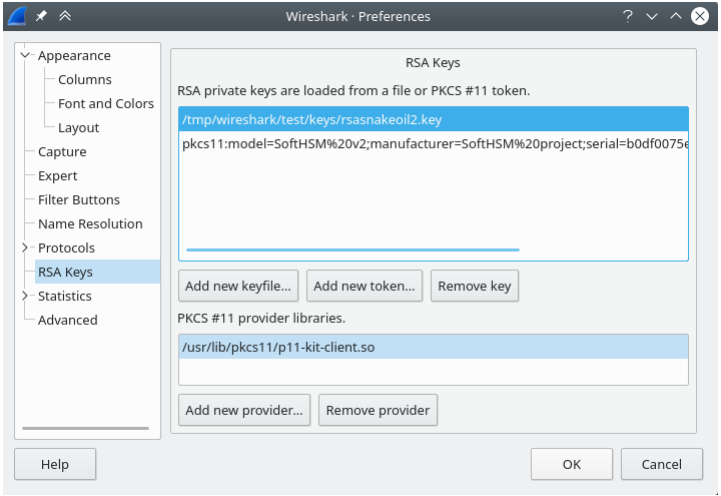
[3] `https://gist.github.com/Lekensteyn/f64ba6d6d2c6229d6ec444647979ea24`

- Symmetric encryption: sender and receiver have the same secret key.
- Authenticated Encryption with Additional Data (**AEAD**) added in TLS 1.2: AES-GCM, ChaCha20-Poly1305.
- Legacy (TLS $\leq$1.2): combine ciphers such as AES-CBC or RC4 with a Hashed Message Authentication Code (HMAC): HMAC-SHA256, HMAC-SHA1.
- Modern symmetric encryption is already post-quantum secure.

- Public-key cryptography: different private and public key. Private encryption/signing key. Public decryption/verification key.
- Digital signature algorithms: RSA, **ECDSA**.
- Key agreement or key exchange (KEX): RSA (encrypt premaster secret against server key), **ECDHE** (Elliptic Curve Diffie-Hellman with ephemeral keys).
- Classical signature and key agreement algorithms are not PQ-secure.

- Client generates random premaster secret and encrypts it using server certificate.
- Server decrypts it using the RSA private key matching the certificate.
- Not forward secret. A single private RSA key file can decrypt all recorded traffic.
- Limitations:
  - Requires server admin to provide the key file.
  - Requires **TLS_RSA**_WITH_AES_128_CBC_SHA ciphers, not TLS_EC**DHE**_...
  - Does not work with session resumption.
  - Does not work with TLS 1.3.
- Example with SSL 3.0 (2006): rsasnakeoil2.pcap and rsasnakeoil2.key.

RSA Keys configuration



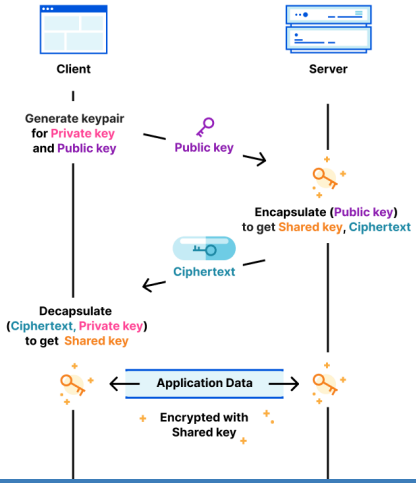
- Not to be confused with *(Pre)-Master-Secret log filename*.
- Accepts PEM-encoded or PKCS#12 key file.
- PKCS#11 token and HSM support.
- `tshark -ouat:rsa_keys:'"rsa.key","password"'`

- Client generates new DH keypair, sends public DH key to server.
- Server generates new DH keypair, sends public DH key to client. Server **signs** it using private RSA/ECDSA key matching the certificate.
- Each side combines their own private key with the peer public key: shared secret.
- Each side throws away their ephemeral DH private key for perfect forward secrecy.
- Works with all TLS versions, including TLS 1.3. Example: tls12-dsb.pcapng
- Diffie-Hellman key exchange and RSA/ECDSA signatures are not PQ-secure.

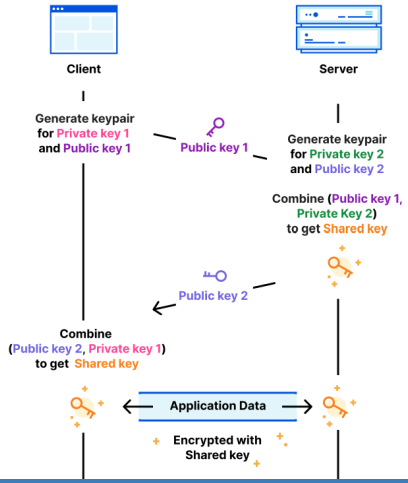
		Size (bytes)		CPU time (lower is better)	
	PQ	**Public key**	**Signature**	**Signing**	**Verification**
Ed25519	❌	32	64	1 (baseline)	1 (baseline)
RSA-2048	❌	256	256	70	0.3
Dilithium2	✅	1,312	2,420	4.8	0.5
Falcon512	✅	897	666	8*	0.5
SPHINCS⁺128s	✅	32	7,856	8,000	2.8
SPHINCS⁺128f	✅	32	17,088	550	7

Source: `https://blog.cloudflare.com/nist-post-quantum-surprise/` (2022)

Key Encapsulation Mechanism (KEM)



Diffie–Hellman (DH)



- Hybrid key agreement: Combine shared secrets from classic ECDHE (X25519) and post-quantum Kyber768 draft version.
- At least as secure as current X25519 deployments.
- Kyber is the basis for the future NIST FIPS 203 standard, *Module-Lattice-Based Key-Encapsulation Mechanism* (ML-KEM)[4].

[4] Initial Public Draft: `https://csrc.nist.gov/pubs/fips/203/ipd` (2023)

Group name	Public key size Client	Server	CPU time Client	Server
ECDHE: X25519	32		1 (baseline)	
ECDHE: NIST P-256	65		3.25	
ECDHE: NIST P-384	97		50.4	
ECDHE: NIST P-521	133		116.7	
PQ: Kyber768	1184	1088	5.53	3.53
Hybrid: X25519Kyber768Draft00	1216	1120	6.53	4.53

- Lower CPU time is better.
- Note: optimized Kyber768 versions are even faster than P-256.

Group name	Group ID	Public key size Client	Server
X25519	29, 0x001d	32	
NIST P-256	23, 0x0017	65	
NIST P-384	24, 0x0018	97	
NIST P-521	25, 0x0019	133	
X25519Kyber768Draft00	25497, 0x6399	1216	1120

```
▾ Extension: key_share (len=1263) X25519Kyber768Draft00, x25519
    Type: key_share (51)
    Length: 1263
  ▾ Key Share extension
      Client Key Share Length: 1261
    ▸ Key Share Entry: Group: Reserved (GREASE), Key Exchange length: 1
    ▾ Key Share Entry: Group: X25519Kyber768Draft00, Key Exchange length: 1216
        Group: X25519Kyber768Draft00 (25497)
        Key Exchange Length: 1216
        Key Exchange: 91299366af91cdb945067ccd9ee60bdae028af3fc8dc7bea823930946
    ▸ Key Share Entry: Group: x25519, Key Exchange length: 32
```

- Servers:
  - Cloudflare enabled PQ KEX in 2022 (about 20% Internet), see `https://pq.cloudflareresearch.com` or try `https://wireshark.org`
  - Google enabled support server-side in 2023.
- Clients:
  - Google Chrome 124 (April 2024): enabled by default. See *TLS 1.3 hybridized Kyber support* at `chrome://flags/#enable-tls13-kyber`.
  - Mozilla Firefox 124 (March 2024): set `security.tls.enable_kyber` to `true` via `about:config`. For QUIC, `network.http.http3.enable_kyber` (FF 128).
- `https://lekensteyn.nl/files/captures/chromium119-dsb.pcapng`
- `https://lekensteyn.nl/files/captures/firefox127-pq-dsb.pcapng`

- Locate Client and Server Hello messages: `tls.handshake.type in {1, 2}`
- For PQ KEX, both client and server TLS extensions must have:
  - Supported Versions with TLS 1.3.
  - Supported Groups with X25519Kyber768Draft00 (25497).
  - Key Shares with X25519Kyber768Draft00.
- QUIC: runs over UDP instead of TCP. Uses TLS 1.3 for security.
- Match TLS Server Name with: `tls.handshake.extensions_server_name`
- Use stream index for linking packets via Custom column:
  - `tcp.stream or quic.connection.number or udp.stream`
- Use Ctrl + , and Ctrl + . to move to the previous/next packet in a conversation.

- Client or server were not properly configured with PQ support.
- TLS 1.3 is not enabled or TLS 1.2 or older is forced.
- The wrong server software was targeted by the client.
- An intercepting TLS middlebox was in use that did not support PQ.
- Bug in servers causing TCP resets for large Client Hello: `https://tldr.fail/`
- Bug in Rustls servers with Hello Retry Request.

- Maximum Transmission Unit (MTU): typically 1500 for Ethernet. Can be lower due to tunneling/VPN overhead.
- Client connects, but during the TLS handshake times out waiting for the server.
- Client capture shows that the TCP handshake succeeds, but
  - Case 1: TLS Client Hello is sent, but never ACKed.
  - Case 2: TLS Server Hello is partially returned.[5] Check TCP sequence numbers.
- Solution: reduce MTU or apply TCP Maximum Segment Size (MSS) clamping.

[5] `https://lekensteyn.nl/files/captures/tls-server-mtu-issue.pcap`

- If a TLS 1.3 server prefers a different key exchange group, it can send a Hello Retry Request (HRR).
- Client receives a TLS alert (Illegal Parameter) during the TLS handshake.
- Affects servers written in the Rust programming language using rustls.[6]
- Fixed in rustls 0.20.9 and 0.21.7 (August 2023).
- Servers must copy client Session ID into HRR to simulate TLS 1.2 session resumption for *middlebox compatibility mode*.
- `https://lekensteyn.nl/files/captures/time-hrr-rustls-bug.pcapng`

[6] `https://github.com/rustls/rustls/issues/1424`

- Cloudflare requests to origin servers supports PQ.[7]
- It can directly send the PQ key share ("preferred mode").
- Or advertise PQ support, but initially send X25519 ("supported mode").
- The latter can trigger a Hello Retry Request to ask the client to retry with the PQ key share. Adds one extra roundtrip.
- `https://lekensteyn.nl/files/captures/pq-origin-dsb.pcapng`

[7] `https://blog.cloudflare.com/post-quantum-to-origins/`

- Previous methods were passive, they preserve the client-server behavior.
- Decryption without modifying workstations or smartphones requires active interception, an man-in-the-middle (MITM) attack.
- Caveat: active interception can affect the investigation. Different TLS parameters can be negotiated, TLS Client Authentication (mutual TLS) breaks, HTTP headers can change, certificate pinning result in new failures.
- Client talk to a proxy server which terminates TLS. The proxy starts a new TLS connection with the original server and forwards re-encrypted traffic.
- Typically a custom Root Certificate Authority (CA) certificate is installed on clients. Middlebox uses the corresponding CA private key to generate new certificates on-the-fly and serve these to clients.
- See `https://mitmproxy.org/`. Supports SSLKEYLOGFILE too!

- Post-quantum cryptography is here to protect data in the future.
- Use a key log file to enable TLS decryption in Wireshark.
- Embed these secrets in a pcapng file for easier distribution.
- Use the latest Wireshark version for the best results.
- See current PQ adoption on Cloudflare Radar and `https://pq.cloudflareresearch.com`
- For a more detailed background and key extraction from other applications, see `https://lekensteyn.nl/files/wireshark-ssl-tls-decryption-secrets-sharkfest18eu.pdf`

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