Post-Quantum TLS without handshake signatures

Peter Schwabe, Douglas Stebila, Thom Wiggers

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TLS 1.3 Handshake

Client | **Server**

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

TCP SYN $\longrightarrow$

$\longleftarrow$ TCP SYN-ACK

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

g^x $\longrightarrow$

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

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

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

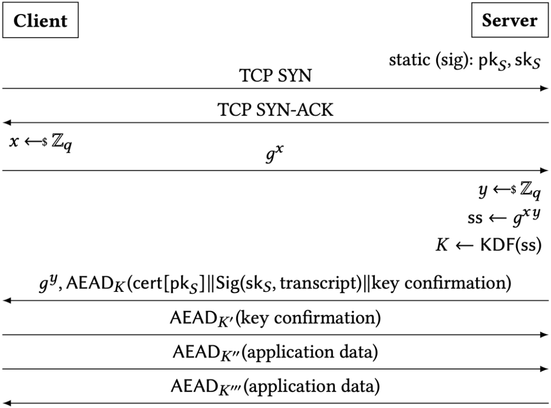
$\longleftarrow$ $g^y, \mathsf{AEAD}_K(\mathsf{cert}[\mathsf{pk}_S] \| \mathsf{Sig}(\mathsf{sk}_S, \text{transcript}) \| \text{key confirmation})$

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

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

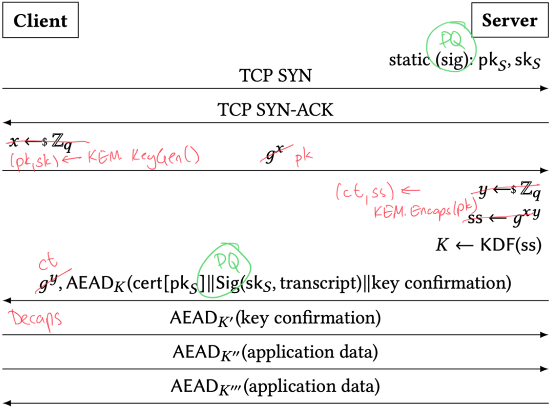
$\longleftarrow$ $\mathsf{AEAD}_{K'''}(\text{application data})$

TLS 1.3 Handshake



- Key exchange: Diffie–Hellman
- Authentication: Signatures

Post-Quantum TLS 1.3 Handshake



- Key exchange: Key-Encapsulation Mechanisms
- Authentication: Post-Quantum Signatures

Post-Quantum TLS 1.3

- Put post-quantum KEMs in TLS Key exchange

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Done, right?

Problem

Post-Quantum signatures are…

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Problem

Post-Quantum signatures are…

- quite a bit bigger than KEMs
- quite a bit slower than KEMs
- quite a bit of extra code

Use PQ KEMs for authentication instead

KEM

Definition (Key Encapsulation Mechanism (KEM))

- $(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{KEM.Keygen}()$
- $(\mathsf{ss}, \mathsf{ct}) \leftarrow \mathsf{KEM.Encapsulate}(\mathsf{pk})$
- $\mathsf{ss} \leftarrow \mathsf{KEM.Decapsulate}(\mathsf{ct}, \mathsf{sk})$

Example

To authenticate Douglas to Peter

Peter		**Douglas**
$(\mathsf{ss}, \mathsf{ct}) \leftarrow \mathsf{KEM.Encapsulate}(\mathsf{pk}_{\mathsf{Douglas}})$		
	$\xrightarrow{\mathsf{ct}}$	
		$\mathsf{ss} \leftarrow \mathsf{KEM.Decapsulate}(\mathsf{ct}, \mathsf{sk}_{\mathsf{Douglas}})$
$K \leftarrow \mathsf{KDF}(\mathsf{ss})$		$K \leftarrow \mathsf{KDF}(\mathsf{ss})$
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KEM authentication in TLS

Problem

- In TLS, the client doesn't already have the public key of the server!
- To put this in TLS 1.3, we need an extra roundtrip!
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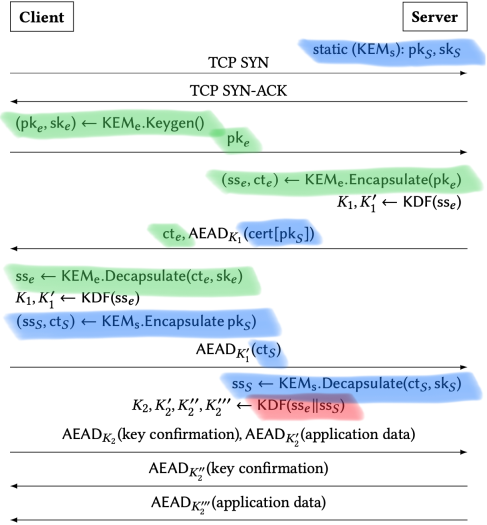
Seen in HMQV (DH), BCGP09 & FSXY12 (KEMs), ..., Signal, Noise, Wireguard, ...

KEMTLS

- Ephemeral key exchange
- Static-KEM authentication
- Combine shared secrets
- Allow client to send application data before receiving server's key confirmation



Client **Server**

static (KEM_s): pk_S, sk_S

TCP SYN →

← TCP SYN-ACK

$(pk_e, sk_e) \leftarrow \mathsf{KEM}_e.\mathsf{Keygen}()$

pk_e →

$(ss_e, ct_e) \leftarrow \mathsf{KEM}_e.\mathsf{Encapsulate}(pk_e)$

$K_1, K_1' \leftarrow \mathsf{KDF}(ss_e)$

← $ct_e, \mathsf{AEAD}_{K_1}(cert[pk_S])$

$ss_e \leftarrow \mathsf{KEM}_e.\mathsf{Decapsulate}(ct_e, sk_e)$

$K_1, K_1' \leftarrow \mathsf{KDF}(ss_e)$

$(ss_S, ct_S) \leftarrow \mathsf{KEM}_s.\mathsf{Encapsulate}\, pk_S)$

$$\xleftarrow{\quad \mathsf{ct}_e,\ \mathsf{AEAD}_{K_1}(\mathsf{cert}[\mathsf{pk}_S]) \quad}$$

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

$$K_1, K_1' \leftarrow \mathsf{KDF}(\mathsf{ss}_e)$$

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

$$\xrightarrow{\quad \mathsf{AEAD}_{K_1'}(\mathsf{ct}_S) \quad}$$

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

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

$$\xrightarrow{\quad \mathsf{AEAD}_{K_2}(\text{key confirmation}),\ \mathsf{AEAD}_{K_2'}(\text{application data}) \quad}$$

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

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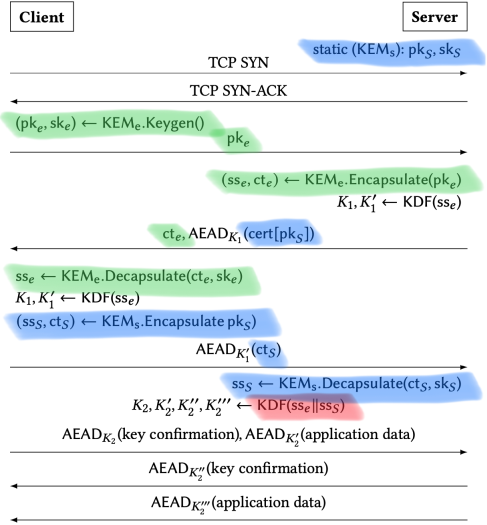

Sending application data before FIN

The client sends data before receiving `ServerFinished`.

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- Only to whatever algorithms the client advertised in `ClientHello`
  - Don't support pre-quantum in KEMTLS

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- Can't downgrade to signed TLS 1.3
  - TLS 1.3 handshake signature stops the attack
- Active adversary might try to downgrade first client-to-server flow
- Only to whatever algorithms the client advertised in `ClientHello`
  - Don't support pre-quantum in KEMTLS
- The handshake will no longer sucessfully complete
  - `ServerFinished` reveals the downgrade unless MAC, KEM, KDF or hash are broken *at time of attack*
  - Once `SF` is received: retroactive full downgrade resilience
  - You also get upgraded from weak to full forward secrecy at this stage

Choosing algorithms

Ephemeral Key Exchange

- KEM with IND-1CCA security
- Ideally fast with small pk $+$ ct

KEM for server authentication

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Root CA certificate

- Already present on client
- Only care about signature size

Choosing algorithms

Ephemeral Key Exchange

- KEM with IND-1CCA security
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KEM for server authentication

- KEM with IND-CCA security
- Ideally fast with small pk + ct

Intermediate CA certificate

- Small public key + signature size

Root CA certificate

- Already present on client
- Only care about signature size

Scenarios

1. Minimize size when intermediate certificate transmitted
2. Minimize size when intermediate certificate not transmitted (cached)
3. Use solely NTRU assumptions
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		KEX	HS Auth	Int. CA. crt	CA crt
1	PQTLS	SIKE	Falcon	$\text{XMSS}_s^{\text{MT}}$	GeMMS
	KEMTLS	SIKE	SIKE	$\text{XMSS}_s^{\text{MT}}$	GeMMS
2	PQTLS	SIKE	Falcon	GeMMS	GeMMS
	KEMTLS	SIKE	SIKE	GeMMS	GeMMS
3	PQTLS	NTRU	Falcon	Falcon	Falcon
	KEMTLS	NTRU	NTRU	Falcon	Falcon
4	PQTLS	Kyber	Dilithium	Dilithium	Dilithium
	KEMTLS	Kyber	Kyber	Dilithium	Dilithium

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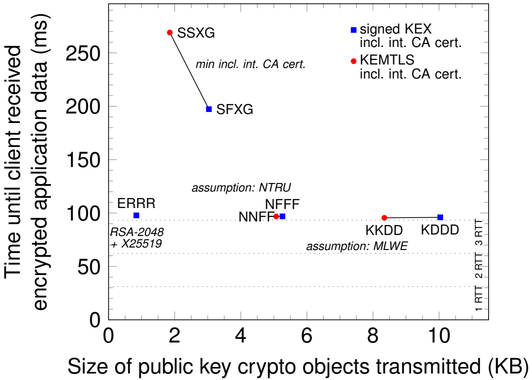
	KEMTLS	SIKE	SIKE	$\text{XMSS}_s^{\text{MT}}$	GeMMS	SSXG
2	PQTLS	SIKE	Falcon	GeMMS	GeMMS	SFGG
	KEMTLS	SIKE	SIKE	GeMMS	GeMMS	SSGG
3	PQTLS	NTRU	Falcon	Falcon	Falcon	NFFF
	KEMTLS	NTRU	NTRU	Falcon	Falcon	NNFF
4	PQTLS	Kyber	Dilithium	Dilithium	Dilithium	KDDD
	KEMTLS	Kyber	Kyber	Dilithium	Dilithium	KKDD

Comparision[1]

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

<u>D</u>ilithium
<u>F</u>alcon
<u>G</u>eMMS
<u>K</u>yber
<u>N</u>TRU
<u>S</u>IKE
<u>X</u>MSS$_s^{MT}$



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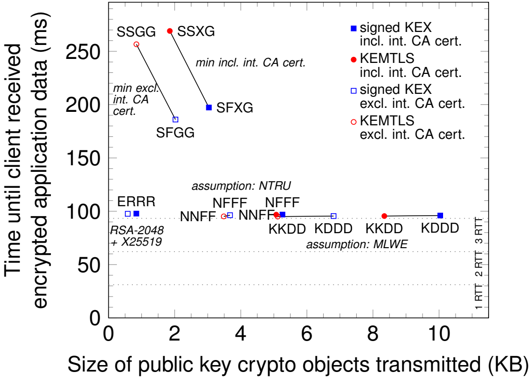

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Observations

- Size-optimized KEMTLS requires $<$½ communication of size-optimized PQ signed-KEM
- Speed-optimized KEMTLS uses 90
- No extra round trips required until client starts sending application data
- Smaller trusted code base (no signature generation on client/server)

FAQ

- Client authentication?
  - We provide a sketch in Appendix D, but mostly leave it for future work
  - Naive way does require a full additional round-trip
- What about TLS 1.3 0-RTT?
  - 0-RTT is for resumption. You can do the same thing in KEMTLS .
  - We see opportunities for more efficient handshakes when resuming or in scenarios with pre-distributed KEM public keys.
- Server can't send application data in its first TLS flow. Will that break HTTP/3 where the server sends a `SETTINGS` frame?
  - Could be included in an extension as a server-side variant of ALPN
- How do you do certificate lifecycle management (issuance, revocation) with KEM public keys?
  - At first glance many of these issues seem non-trivial: currently these assume the public key can be used for signatures in some way
  - Another good direction for future work

Post-Quantum TLS without Handshake signatures

Douglas Stebila, Peter Schwabe, Thom Wiggers

- Implicit authentication via KEMs
- Preserve client ability to do request after 1RTT
- Saves bytes on the wire and server CPU cycles

- ACM CCS 2020 doi: 10.1145/3372297.3423350
- Full version with proofs: ia.cr/2020/534
- Experimental implementations and datasets: github.com/thomwiggers/kemtls-experiment

Appendix

Communications sizes

		Abbrv.	KEX (pk+ct)	Excluding intermediate CA certificate: HS auth (ct/sig)	Leaf crt. subject (pk)	Leaf crt. (signature)	Sum excl. int. CA cert.	Including intermediate CA certificate: 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 (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	2711
TLS 1.3 (Signed KEX)	**Min. incl. int. CA cert.**	SFXG	SIKE 405	Falcon 690	Falcon 897	$XMSS_s^{MT}$ 979	**2971**	$XMSS_s^{MT}$ 32	GeMSS 32	**3035**	GeMSS 352180	4056
TLS 1.3 (Signed KEX)	**Min. excl. int. CA cert.**	SFGG	SIKE 405	Falcon 690	Falcon 897	GeMSS 32	**2024**	GeMSS 352180	GeMSS 32	**354236**	GeMSS 352180	355737
TLS 1.3 (Signed KEX)	**Assumption: MLWE+MSIS**	KDDD	Kyber 1536	Dilithium 2044	Dilithium 1184	Dilithium 2044	**6808**	Dilithium 1184	Dilithium 2044	**10036**	Dilithium 1184	11094
TLS 1.3 (Signed KEX)	**Assumption: NTRU**	NFFF	NTRU 1398	Falcon 690	Falcon 897	Falcon 690	**3675**	Falcon 897	Falcon 690	**5262**	Falcon 897	6227
KEMTLS	**Min. incl. int. CA cert.**	SSXG	SIKE 405	SIKE 209	SIKE 196	$XMSS_s^{MT}$ 979	**1789**	$XMSS_s^{MT}$ 32	GeMSS 32	**1853**	GeMSS 352180	2898
KEMTLS	**Min. excl. int. CA cert.**	SSGG	SIKE 405	SIKE 209	SIKE 196	GeMSS 32	**842**	GeMSS 352180	GeMSS 32	**353054**	GeMSS 352180	354578
KEMTLS	**Assumption: MLWE+MSIS**	KKDD	Kyber 1536	Kyber 736	Kyber 800	Dilithium 2044	**5116**	Dilithium 1184	Dilithium 2044	**8344**	Dilithium 1184	9398
KEMTLS	**Assumption: NTRU**	NNFF	NTRU 1398	NTRU 699	NTRU 699	Falcon 690	**3486**	Falcon 897	Falcon 690	**5073**	Falcon 897	6066

Time measurements

		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	**97.6**	35.4	66.6	**97.8**	35.6	397.1	**593.3**	201.3	398.2	**594.3**	202.3
	SFXG	40.058	21.676	40.094	21.676	165.8	**196.9**	134.0	166.2	**197.3**	134.4	482.1	**678.4**	285.8	482.5	**678.8**	286.2
	SFGG	34.104	21.676	34.141	21.676	154.9	**186.0**	123.1	259.0	**290.2**	227.1	473.7	**669.8**	277.5	10936.3	**11902.5**	10384.1
	KDDD	0.080	0.087	0.111	0.087	64.3	**95.5**	33.3	64.8	**96.0**	33.8	411.6	**852.4**	446.1	415.9	**854.7**	448.0
	NFFF	0.141	0.254	0.181	0.254	65.1	**96.3**	34.1	65.6	**96.9**	34.7	398.1	**662.2**	269.2	406.7	**842.8**	443.5
KEMTLS	**SSXG**	61.456	41.712	61.493	41.712	202.1	**268.8**	205.6	202.3	**269.1**	205.9	505.8	**732.0**	339.7	506.1	**732.4**	340.1
	SSGG	55.503	41.712	55.540	41.712	190.4	**256.6**	193.4	293.3	**359.5**	296.3	496.8	**723.0**	330.8	10859.5	**11861.0**	10331.7
	KKDD	0.060	0.021	0.091	0.021	63.4	**95.0**	32.7	63.9	**95.5**	33.2	399.2	**835.1**	439.9	418.9	**864.2**	447.6
	NNFF	0.118	0.027	0.158	0.027	63.6	**95.2**	32.9	64.2	**95.8**	33.5	396.2	**593.4**	200.6	400.0	**835.6**	440.2

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629	66.4	**97.6**	35.4	66.6	**97.8**	35.6	39
676	165.8	**196.9**	134.0	166.2	**197.3**	134.4	48
676	154.9	**186.0**	123.1	259.0	**290.2**	227.1	47
087	64.3	**95.5**	33.3	64.8	**96.0**	33.8	41
254	65.1	**96.3**	34.1	65.6	**96.9**	34.7	39
712	202.1	**268.8**	205.6	202.3	**269.1**	205.9	50
712	190.4	**256.6**	193.4	293.3	**359.5**	296.3	49
021	63.4	**95.0**	32.7	63.9	**95.5**	33.2	39
027	63.6	**95.2**	32.9	64.2	**95.8**	33.5	39

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134.4	482.1	**678.4**	285.8	482.5	**678.8**	286.2
227.1	473.7	**669.8**	277.5	10936.3	**11902.5**	10384.1
33.8	411.6	**852.4**	446.1	415.9	**854.7**	448.0
34.7	398.1	**662.2**	269.2	406.7	**842.8**	443.5
205.9	505.8	**732.0**	339.7	506.1	**732.4**	340.1
296.3	496.8	**723.0**	330.8	10859.5	**11861.0**	10331.7
33.2	399.2	**835.1**	439.9	418.9	**864.2**	447.6
33.5	396.2	**593.4**	200.6	400.0	**835.6**	440.2