Code-based cryptography for secure communication

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- We encrypt a short symmetric key and use that to encrypt the actual message.
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- A key-encapsulation mechanism requires 3 algorithms:
  1. Key generation, generating a public-key private-key pair.
  2. Encapsulation, taking a public key, producing key $k$ and ciphertext. $k$ is then used in symmetric crypto.
  3. Decapsulation, taking a private key and a ciphertext, producing key.
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     $k$ is then used in symmetric crypto.
  3. Decapsulation, taking a private key and a ciphertext, producing key.
- Can think of DH as a KEM:
  \[
  \text{KEM} - \text{Enc}(g^a) = (g^{ra}, g^r) = (k, c)
  \]
- Anna-Lena Horlemann explained Niederreiter for encryption.
- Niederreiter as KEM takes public key, picks random vector of length $n$, weight $t$.  

Tanja Lange  

Code-based cryptography for secure communication
How does TLS (https) work?

Client

\((sk_C, pk_C) \leftarrow \$ KGen\)

\(pk_C\)

\(\rightarrow\)

\(pk_S\)

\(\leftarrow\)

\(k \leftarrow \text{DH}(sk_C, pk_S)\)

\(k \leftarrow \text{DH}(sk_C, pk_S)\)

stuff encrypted using \(k\)

proves \(C\) knows \(k\)

\(\Sigma \leftarrow \text{Sig}(\text{everything sent so far})\)

\(\leftarrow\)

\(\Sigma\)

stuff encrypted using \(k\)

this uses a long-term signing key
How does PQC affect protocols?

▶ Length fields don’t fit.

- Restrict to systems that fit, if any, or keep pre-quantum algorithm next to PQC one, putting PQC part into the payload.
- Speed, resources. Combined schemes take about twice the time. Most experiments don’t look so devastating.
- Interface mismatch – KEM instead of DH. Shoehorning PQC into current systems may prioritize weaker systems.
- Validation and certification schemes are not updated. Combine pre- and post-quantum schemes, certification only applies to pre-quantum scheme. For such hybrid schemes, ensure that as strong as strongest not as weak as weakest.
- New security assumptions, new proofs, lots of new code.
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- New security assumptions, new proofs, lots of new code.
Encryption (KEM): ciphertext size (vertical) vs. public-key size (horizontal)
Signatures: signature size (vertical) vs. public-key size (horizontal)
Deployment issues & solutions

- Different recommendations for rollout in different risk scenarios:
  - Use most efficient systems with ECC or RSA, to ease usage and gain familiarity.
  - Use most conservative systems (possibly with ECC), to ensure that data really remains secure.

- Protocol integration and implementation problems:
  - Key sizes or message sizes are larger for post-quantum systems, but IPv6 guarantees only delivery of $\leq 1280$-byte packets, TLS software has length limits, etc.
  - Google experimented with larger keys and noticed delays and dropped connections.
  - Long-term keys require extra care (reaction attacks).

- Some libraries exist, quality is getting better.

- Google and Cloudflare are running some experiments of including post-quantum systems into TLS.
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- Google and Cloudflare are running some experiments of including post-quantum systems into TLS.

- These all use lattice based schemes. How about the code-based finalist?
NIST PQC submission Classic McEliece

No patents.
Shortest ciphertexts.
Fast open-source constant-time software implementations.
Very conservative system, expected to last; has strongest security track record.

Sizes with similar post-quantum security to AES-128, AES-192, AES-256:

<table>
<thead>
<tr>
<th>Metric</th>
<th>mceliece348864</th>
<th>mceliece460896</th>
<th>mceliece6960119</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public-key size</td>
<td>261120 bytes</td>
<td>524160 bytes</td>
<td>1047319 bytes</td>
</tr>
<tr>
<td>Secret-key size</td>
<td>6452 bytes</td>
<td>13568 bytes</td>
<td>13908 bytes</td>
</tr>
<tr>
<td>Ciphertext size</td>
<td>128 bytes</td>
<td>188 bytes</td>
<td>226 bytes</td>
</tr>
<tr>
<td>Key-generation time</td>
<td>52415436 cycles</td>
<td>181063400 cycles</td>
<td>417271280 cycles</td>
</tr>
<tr>
<td>Encapsulation time</td>
<td>43648 cycles</td>
<td>77380 cycles</td>
<td>143908 cycles</td>
</tr>
<tr>
<td>Decapsulation time</td>
<td>130944 cycles</td>
<td>267828 cycles</td>
<td>295628 cycles</td>
</tr>
</tbody>
</table>

See https://classic.mceliece.org for authors, details & parameters.
Key issues for McEliece
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BIG PUBLIC KEYS.
Key issues for McEliece

Users send big data anyway. We have lots of bandwidth. Maybe 1MB keys are okay. Each client spends a small fraction of a second generating new ephemeral 1MB key.
Users send big data anyway. We have lots of bandwidth. Maybe 1MB keys are okay. Each client spends a small fraction of a second generating new ephemeral 1MB key. But: If any client is allowed to send a new ephemeral 1MB McEliece key to server, an attacker can easily flood server’s memory. This invites DoS attacks. (DoS = Denial of Service)
Key issues for McEliece

Users send big data anyway. We have lots of bandwidth. Maybe 1MB keys are okay. Each client spends a small fraction of a second generating new ephemeral 1MB key. But: If any client is allowed to send a new ephemeral 1MB McEliece key to server, an attacker can easily flood server’s memory. This invites DoS attacks. (DoS = Denial of Service)

Our goal: Eliminate these attacks by eliminating all per-client storage on server.
Goodness, what big keys you have!

Public keys look like this:

$$K = \begin{pmatrix}
1 & 0 & \ldots & 0 & 1 & \ldots & 1 & 0 & 1 \\
0 & 1 & \ldots & 0 & 0 & \ldots & 0 & 1 & 1 \\
\vdots & \vdots & \ddots & \vdots & 1 & \ldots & 1 & 1 & 0 \\
0 & 0 & \ldots & 1 & 0 & \ldots & 1 & 1 & 1
\end{pmatrix}$$

Left part is \((n - k) \times (n - k)\) identity matrix (no need to send).
Right part is random-looking \((n - k) \times k\) matrix.
E.g. \(n = 6960, k = 5413\), so \(n - k = 1547\).
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Encryption xors secretly selected columns, e.g.

\[
\begin{pmatrix}
0 \\
1 \\
0 \\
0
\end{pmatrix} + \begin{pmatrix}
1 \\
0 \\
1 \\
0
\end{pmatrix} + \begin{pmatrix}
0 \\
1 \\
1 \\
1
\end{pmatrix} + \begin{pmatrix}
1 \\
1 \\
0 \\
1
\end{pmatrix} = \begin{pmatrix}
0 \\
1 \\
0 \\
0
\end{pmatrix}
\]
Can servers avoid storing big keys?

\[ K = \begin{pmatrix}
1 & 0 & \ldots & 0 & 1 & \ldots & 1 & 0 & 1 \\
0 & 1 & \ldots & 0 & 0 & \ldots & 0 & 1 & 1 \\
\vdots & \vdots & \ddots & \vdots & 1 & \ldots & 1 & 1 & 0 \\
0 & 0 & \ldots & 1 & 0 & \ldots & 1 & 1 & 1 \\
\end{pmatrix} = (I_{n-k} | K') \]

Encryption xors secretly selected columns.

With some storage and trusted environment:
Receive columns of $K'$ one at a time, store and update partial sum.
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On the real Internet, without per-client state:
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0 & 1 & \ldots & 0 & 0 & \ldots & 0 & 1 & 1 \\
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Encryption xors secretly selected columns.

With some storage and trusted environment:
Receive columns of $K'$ one at a time, store and update partial sum.

On the real Internet, without per-client state:
Don’t reveal intermediate results!
Which columns are picked is the secret message!
Intermediate results show whether a column was used or not.
McTiny

Partition key

\[
K' = \begin{pmatrix}
K_{1,1} & K_{1,2} & K_{1,3} & \ldots & K_{1,\ell} \\
K_{2,1} & K_{2,2} & K_{2,3} & \ldots & K_{2,\ell} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
K_{r,1} & K_{r,2} & K_{r,3} & \ldots & K_{r,\ell}
\end{pmatrix}
\]

- Each submatrix \(K_{i,j}\) small enough to fit (including header) into network packet.
- Client feeds the \(K_{i,j}\) to server & handles storage for the server.
- Server computes \(K_{i,j}e_j\), puts result into cookie.
- Cookies are encrypted by server to itself using some temporary symmetric key (same key for all server connections).
  No per-client memory allocation.
- Cookies also encrypted & authenticated to client.
- Client sends several \(K_{i,j}e_j\) cookies, receives their combination.
- More stuff to avoid replay & similar attacks.
Each submatrix $K_{i,j}$ small enough to fit (including header) into network packet.

Client feeds the $K_{i,j}$ to server & handles storage for the server.

Server computes $K_{i,j}e_j$, puts result into cookie.

Cookies are encrypted by server to itself using some temporary symmetric key (same key for all server connections).

No per-client memory allocation.

Cookies also encrypted & authenticated to client.

Client sends several $K_{i,j}e_j$ cookies, receives their combination.

More stuff to avoid replay & similar attacks.

Several round trips, but no per-client state on the server.
Packet sizes in each phase of mceliece6960119

<table>
<thead>
<tr>
<th>phase</th>
<th>bytes/packet</th>
<th>packets</th>
<th>bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>query</td>
<td>810</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>reply</td>
<td>121</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>query</td>
<td>1226</td>
<td>952</td>
</tr>
<tr>
<td></td>
<td>reply</td>
<td>140</td>
<td>952</td>
</tr>
<tr>
<td>2</td>
<td>query</td>
<td>1185</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>reply</td>
<td>133</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>query</td>
<td>315</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>reply</td>
<td>315</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>queries</td>
<td>971</td>
<td>1188422</td>
</tr>
<tr>
<td></td>
<td>replies</td>
<td>971</td>
<td>135977</td>
</tr>
</tbody>
</table>

Entries count only application-layer data and not counting UDP/IP/Ethernet overhead.

A public key is 1 047 319 bytes.
Measurements of our software (https://mctiny.org)

Client time vs. bytes sent, bytes acknowledged, bytes in acknowledgments.
Curve shows packet pacing from our new user-level congestion-control library.
WireGuard

- WireGuard is a VPN protocol.
- VPN stands for Virtual Private Network.
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- VPN stands for Virtual Private Network. (Not that that explains much)
- Relevant distinction from TLS scenario: Client connects to known, fixed server.
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- WireGuard is a VPN protocol.
- VPN stands for Virtual Private Network. (Not that that explains much)
- Relevant distinction from TLS scenario: Client connects to known, fixed server.
- In WireGuard the server is known by a long-term DH key.
- This public key is exchanged out of band.
Client
knows $LTpk_S$

\[
\text{(sk}_C, \text{pk}_C) \leftarrow \$ KGen
\]

\[
k_1 \leftarrow DH(\text{sk}_C, LTpk_S)
\]

\[
\frac{pk_C}{\text{something with } k_1}
\]

\[
k_1 \leftarrow DH(LTkS S, \text{pk}_C), \text{check } k_1
\]

\[
(\text{sk}_S, \text{pk}_S) \leftarrow \$ KGen
\]

\[
k_2 \leftarrow H(k_1, DH(\text{sk}_S, \text{pk}_C))
\]

\[
\frac{pk_S}{\text{something with } k_2}
\]

\[
k_2 \leftarrow H(k_1, DH(\text{sk}_C, \text{pk}_S))
\]

\[
\text{content encrypted with } k_2
\]

\[
\text{or keys derived from } k_2
\]
'WireGuard' with KEMs

Client
knows KEM LTpk_S

Server
has KEM LTsk_S, LTpk_S

Actual start

$$(sk_C, pk_C) \leftarrow \text{KGen}$$

$$(k_1, c_1) \leftarrow \text{KEM–Enc}(LTpk_S)$$

$$k_1 \leftarrow \text{KEM–Dec}(LTsk_S, c_1)$$

$$pk_C \leftarrow \text{Dec}(k_1, \text{Enc}(k_1, pk_C))$$

$$(k'_2, c_2) \leftarrow \text{KEM–Enc}(pk_C)$$

stuff to verify

$$k_2 \leftarrow H(k_1, k'_2)$$

$$k_2 \leftarrow \text{KEM–Dec}(sk_C, c_2)$$

content encrypted with $$k_2$$

or keys derived from $$k_2$$

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Code-based cryptography for secure communication
In Post-Quantum WireGuard the server is known by a long-term KEM key $LT_{pk_S}$. This public key is exchanged out of band.
Post-quantum WireGuard https://eprint.iacr.org/2020/379

- In Post-Quantum WireGuard the server is known by a long-term KEM key $LT_{pk_S}$.
- This public key is exchanged out of band.
- This key can be large, we do not pay for it in bandwidth!
In Post-Quantum WireGuard the server is known by a long-term KEM key $LT_{pk_S}$.
This public key is exchanged out of band.
This key can be large, we do not pay for it in bandwidth!
$c_1$ is a KEM ciphertext, this should be small.
Short-term KEM public key $pk_C$ is sent and should be small.
In Post-Quantum WireGuard the server is known by a long-term KEM key $LT_{pk_S}$.
This public key is exchanged out of band.
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$c_1$ is a KEM ciphertext, this should be small.
Short-term KEM public key $pk_C$ is sent and should be small.
Post-quantum WireGuard uses Classic McEliece for the long-term KEM and lattice-based Saber for the short-term KEM.
This showcases the small ciphertexts of Classic McEliece and does not notice the public-key size.
Different deployment strategy

PQConnect: An Automated Boring Protocol for Quantum-Secure Tunnels

▶ Do not patch PQC onto existing network protocols, but add a new layer with superior security.
Different deployment strategy

PQConnect: An Automated Boring Protocol for Quantum-Secure Tunnels

- Do not patch PQC onto existing network protocols, but add a new layer with superior security.
- Can be gradually deployed.
- Add support for VPN-like tunnels to clients and servers
Different deployment strategy

PQConnect: An Automated Boring Protocol for Quantum-Secure Tunnels

- Do not patch PQC onto existing network protocols, but add a new layer with superior security.
- Can be gradually deployed.
- Add support for VPN-like tunnels to clients and servers but do this to the endpoints, not some intermediate VPN server.
- PQConnect is designed for security, handshake and ratcheting proven using Tamarin prover (formal verification tool).
- Use Curve25519 (pre-quantum) and Classic McEliece (conservative PQC) for long-term identity keys.
- Use Curve25519 (pre-quantum) and lattice-based Streamlined NTRU Prime (PQC) for ephemeral keys.
PQConnect handshake: Nesting schemes

Most conservative system on the outside.

Attacker can see long-term Curve25519 identity key, can break it with a quantum computer, but cannot obtain DH value as client’s share is wrapped.
PQConnect handshake: Handling McEliece keys

- McEliece is used for the long-term key, i.e., this key does not change.
- Store key for frequently visited sites (Google, Gmail, Facebook, Twitter, ...) 
- Link key download to obtaining IP address via DNS lookup.  
  This is how the client know where to connect to. PQConnect piggy-backs on this 
  with a hash of the key and info on where to download the key.
PQConnect handshake: Handling McEliece keys

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- Store key for frequently visited sites (Google, Gmail, Facebook, Twitter, ...)
- Link key download to obtaining IP address via DNS lookup. This is how the client know where to connect to. PQConnect piggy-backs on this with a hash of the key and info on where to download the key.
- Split key as in McTiny, download in small chunks and verify with hash; PQConnect also includes the Curve25519 key (256 bits, just a small corner).
- PQConnect benefits from small McEliece ciphertexts.
- Combine with lattice-based crypto for balance in ciphertext and public key size; security concerns alleviated by nesting.
- More information on protocol: https://research.tue.nl/en/studentTheses/pqconnect
  Paper and software still forthcoming.
Key ratchet advances by message and time

Complete protocol follows picture on previous slide.
All systems linked together to generate initial key $c_0$.
Keys are updated (ratcheted) to protect against later decryption by theft of computer equipment.
Immediately advance ratchet in 3 ways:

- New epoch master key: $c_1$.
- New branch keys: $c_{0,1}, c_{0,2}$.
- New message key: $c'_{0,1}$.

Delete key as soon as no longer needed.
Message keys can deal with delayed transmissions.
Further information

- [https://pqcrypto.org](https://pqcrypto.org) our overview page.
  - PQCRYPTO recommendations.
  - Free software libraries (libpqcrypto, pqm4, pqhw).
  - Many reports, scientific articles, (overview) talks.
- YouTube channel Tanja Lange: Post-quantum cryptography.
- [https://2017.pqcrypto.org/exec](https://2017.pqcrypto.org/exec) and [https://pqcschool.org/index.html](https://pqcschool.org/index.html):
  Executive school (less math, more perspective).
- Quantum Threat Timeline from Global Risk Institute, 2019; 2021 update.
- Status of quantum computer development (by German BSI).
- NIST PQC competition.