The case for ubiquitous transport-level encryption

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Goals

What would it take to encrypt the vast majority of TCP traffic?

1. **Performance.**
   - Fast enough to enable by default on almost all servers.

2. **End-point authentication.**
   - Leverage certificates, cookies, passwords, *etc.*, to achieve best possible security for any given setting.

3. **Compatibility.**
   - Works in existing networks.
   - Works with legacy apps.
Performance today can be pretty bad

Biggest problem: cost of public key cryptography.

Worst case: SSL can be 82x slower than TCP…
Performance today can be pretty bad

Biggest problem: cost of public key cryptography.

Worst case: SSL can be 82x slower than TCP…

- Worst case: tcpcrypt only 3x slower than TCP!
Problem today:
app-level auth divorced from transport

1. SSL encrypts + server auth.

SSL. Authenticate server using certificates

Username: Andrea
Password: w00t

If step 1 fails, step 2 doesn’t help—in fact, it harms.
Problem today: app-level auth divorced from transport

1. SSL encrypts + server auth.


If step 1 fails, step 2 doesn’t help—in fact, it harms.
What’s the best we can do?

Level of security against a network attacker depends on scenario.

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Backwards compatibility issues

Two prevalent ways of encrypting network traffic:

1. At application layer (e.g., SSL).
   - ✓ Works over almost all networks.
   - ✗ Need to modify applications.
   - ✗ Application protocol may not allow incremental deployment.

2. At network layer (e.g., IPSec).
   - ✓ Works with all applications.
   - ✗ Breaks NAT.
   - ✗ Can’t leverage user authentication.

Ubiquitous encryption requires best of both worlds.
tcpcrypt: transport-layer encryption

tcpcrypt: a TCP option for encryption.

1. High server performance: push complexity to clients.

2. Allow applications to authenticate end points.

tcpcrypt overview

- Extend TCP in a compatible way using TCP options.
- Applications use standard BSD socket API.
- New getsockopt for authentication.
- Encryption automatically enabled if both end points support tcpcrypt.
Push expensive operations to clients

Public key operations expensive, but not all equally expensive. RSA-exp3-2048 performance:

<table>
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<tr>
<th>Operation</th>
<th>Latency (ms)</th>
</tr>
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<tbody>
<tr>
<td>Decrypt</td>
<td>10.42</td>
</tr>
<tr>
<td>Encrypt</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Have client do decrypt

- Generate ephemeral key pair
- **public key**
- \( \text{enc}_{\text{pubk}}(\text{master key}) \)
- Generate random master key
- client
- server

Without server authentication, have client decrypt. Lets servers accept connections at 36x rate of SSL.
Link app auth to transport auth

**Session ID**: hook linking tcpencrypt to app-level authentication.
- New `getsockopt` returns non-secret Session ID value.
- Unique for every connection (if one endpoint honest).
- If same on both ends, no man-in-the-middle.

Authenticating the Session ID authenticates the endpoint.
Auth example: batch signing

Tcpcrypt: server signs multiple session IDs at once to amortize RSA cost.
Auth example: batch signing

Tcpcrypt: server signs multiple session IDs at once to amortize RSA cost.

```
SID A
“A” Signed by amazon.com

SID B
“B” Signed by amazon.com
```
Auth example: batch signing

Tcpcrypt: server signs multiple session IDs at once to amortize RSA cost.

```
SID A
SID B
SID C
SID D
“A, B, C, D”
Signed by amazon.com
```

SSL servers must RSA decrypt each client’s secret.

```
enc(secret A)
enc(secret B)
enc(secret C)
enc(secret D)
RSA op.
RSA op.
RSA op.
RSA op.
```

"A, B, C, D" Signed by amazon.com
Auth example: batch signing

Tcpcrypt: server signs multiple session IDs at once to amortize RSA cost.

SSL servers must RSA decrypt each client’s secret.
Key exchange overview

Do you support tcpcrypt?

Yes, and I support RSA

RSA public key

\(\text{enc}_{\text{pubk}}(\text{master key})\)

Generate random master key

Client

Server

Clients periodically generate ephemeral public keys.
tcpcrypt key exchange

SYN

SYN ACK

ACK
tcpcrypt key exchange

- SYN
- SYN
- ACK
- ACK

SYN - CRYPT(HELLO)
probe tcpcrypt

tcpcrypt negotiation encoded in TCP options.
tcpcrypt key exchange

SYN - CRYPT(HELLO)
probe tcpcrypt

SYN ACK - CRYPT(PKCONF)
public key ciphers and key sizes list

ACK - CRYPT(INIT1)
symmetric ciphers and MACs list, nonce, public key

ACK - CRYPT(INIT2)
encrypted client and server nonce (master key)

crypto on

- tcpcrypt negotiation encoded in TCP options.
- INIT1 and INIT2 too long: sent as data invisible to apps.
Key scheduling

Master key is hash of:

- Server and client nonces.
- Public key used and negotiated parameters.

```
Master key
  /\                        /\                        /\                        /\
RX MAC key  hash (HMAC)  RX enc. key  Session ID  TX MAC key  TX enc. key
```

Session caching, like in SSL: on reconnect, establish new keys without explicit key exchange.
Key scheduling

Master key is hash of:

- Server and client nonces.
- Public key used and negotiated parameters.

- Session caching, like in SSL: on reconnect, establish new keys without explicit key exchange.
Session caching

SYN - NEXTK1
New session based on session with ID X

SYN ACK - NEXTK2
OK!

crypto on

ack

Low latency: completes within TCP handshake.
TCP MAC and encryption

<table>
<thead>
<tr>
<th>src port</th>
<th>dst port</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>seq no.</td>
<td></td>
</tr>
<tr>
<td>ack no.</td>
<td></td>
</tr>
<tr>
<td>d.off.</td>
<td>flags</td>
</tr>
<tr>
<td>window</td>
<td>checksum</td>
</tr>
<tr>
<td></td>
<td>urg. ptr.</td>
</tr>
<tr>
<td>options (e.g., SACK)</td>
<td>MAC option</td>
</tr>
<tr>
<td>data</td>
<td></td>
</tr>
<tr>
<td>TCP length</td>
<td></td>
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- Allow NATs: do not MAC ports.
- Prevent replay: MAC extended (implicit) seq. no.
- Prevent truncation / extension: MAC length.
## Implementation

1. Linux kernel implementation: 4,500 LoC.

2. Portable userspace divert socket implementation: 7,000 LoC.
   - Tested on Windows (required implementing divert sockets), Mac OS, Linux and FreeBSD.

3. Binary compatible OpenSSL library that attempts tcpcrypt with batch-signing or falls back to SSL.
Performance overview

Performance considerations when turning encryption on:

1. Does encryption sacrifice request handling throughput? *E.g.*, how many web requests / second can a server handle?

2. Is request latency harmed? *E.g.*, How long does a client need to wait before a web page is displayed?

3. Is data throughput high? What’s the bitrate when downloading?

Hardware: 8-core, 2.66GHz Xeon (2008-era).
Software: Linux kernel implementation.
High connection rate on servers

TCP

98,434

No sessions cached

SSL

754

tcp

27,070

server

Connections/s

0

20000

40000

60000

80000

100000

120000

TCP

tcp
server

SSL
server

Connections/s

98,434

27,070

754
High connection rate on servers

TCP tcpcrypt server

SSL server

Connections/s

98,434
70,044
27,070
39,785
754

No sessions cached
All sessions cached
Low authentication cost

- 25x faster than SSL when batch signing
Web-serve up to 25x faster than SSL

Apache serving a 44 byte static file.

- No server authentication with tcprypt: fair comparison would make tcpcrypt slower.
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<th>LAN connect time (ms)</th>
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<tr>
<td>TCP</td>
<td>0.2</td>
</tr>
<tr>
<td>tcpcrypt cached</td>
<td>0.3</td>
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<td>11.3</td>
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<tr>
<td>SSL cached</td>
<td>0.7</td>
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<tr>
<td>SSL not cached</td>
<td>11.6</td>
</tr>
<tr>
<td>tcpcrypt batch sign</td>
<td>11.2</td>
</tr>
<tr>
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<td>11.4</td>
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Batch signing does not add latency

```
SYN - HELLO
SYN ACK - PKCONF
ACK - INIT1
ACK - INIT2
Signature
```

RSA decrypt start

```
connection ready
```

RSA sign start
Gigabit encryption possible

New CPUs (Westmere) with special AES instructions can saturate 9 Gbit/s networks while encrypting.

![Transfer rate chart](chart.png)
Gigabit encryption possible

New CPUs (Westmere) with special AES instructions can saturate 9 Gbit/s networks while encrypting.
Related work

   - Hard to integrate with application-level authentication.
   - Network compatibility issues: NATs.

2. Application layer solutions: SSL, Opportunistic encryption [Langley].
   - Poor server-side performance.
   - Requires changes to apps and possibly protocol.

3. SSL performance improvements:
   - SSL batching [Shacham & Boneh]: requires different public keys.
   - SSL rebalancing [Castelluccia, Mykletun & Tsudik]: does not leverage app-level authentication.
Conclusion

1. High server performance makes encryption a realistic default.

2. Let applications leverage tcpcrypt to maximize communication security in every setting.

3. Incrementally deployable, compatible with legacy apps, TCP and NATs.

Install tcpcrypt and help encrypt the Internet!

http://tcpcrypt.org