Mathematics and development of fast TLS handshakes

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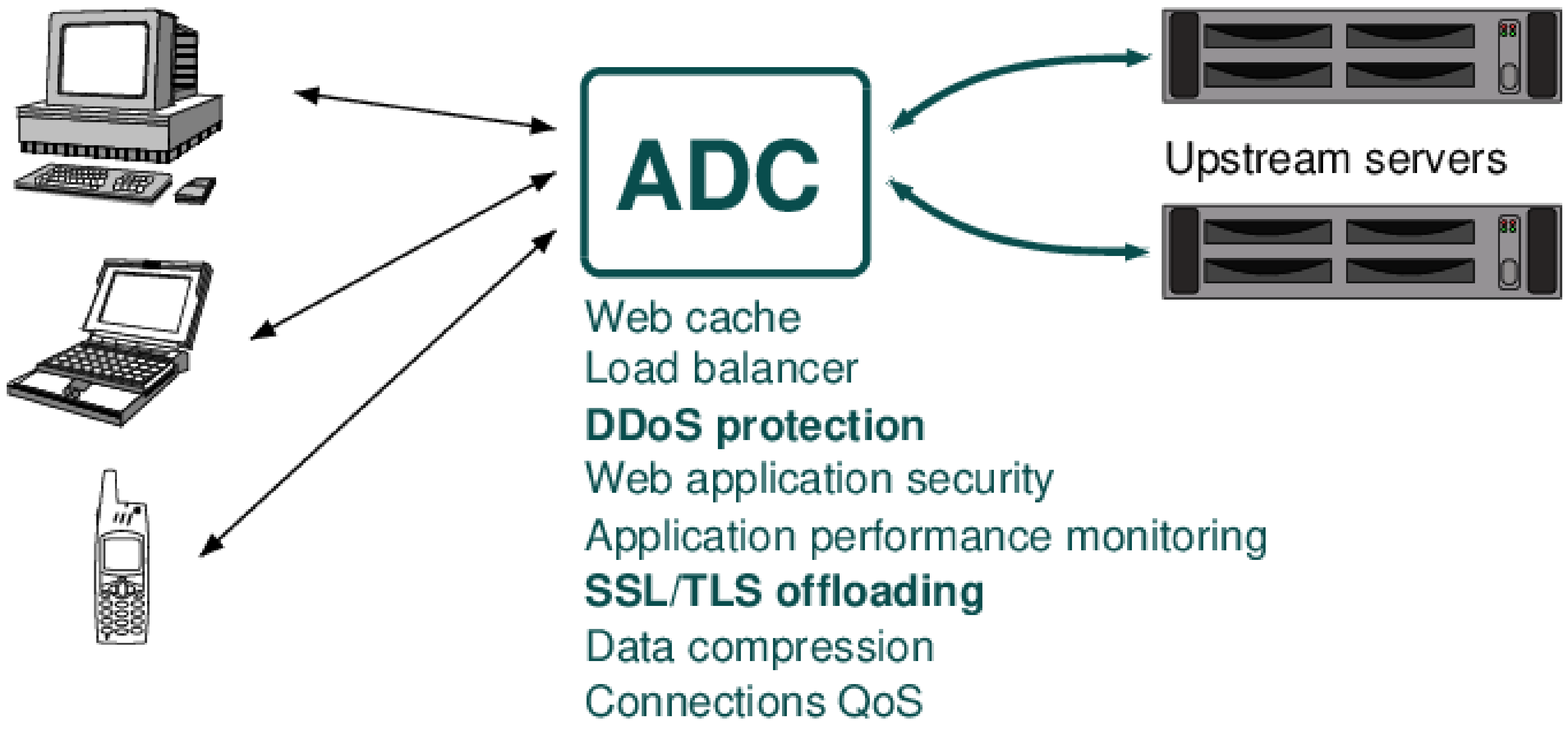
Web content delivery & protection

- 2013: **WAF** development by request of Positive Technologies
  “Visionar” from Gartner magic quadrant’15
  - Web attacks
  - L7 HTTP/HTTPS DDoS attacks
- Nginx, HAProxy, etc. - perfect HTTP proxies, not HTTP filters
- Netfilter works in TCP/IP stack (softirq) => **HTTP(S)/TCP/IP stack**
- **Tempesta FW**:
  - hybrid of HTTP accelerator & firewall
  - **embedded into the Linux TCP/IP stack**

Tempesta TLS

https://netdevconf.info/0x12/session.html?kernel-tls-handhakes-for-https-ddos-mitigation

- Part of **Tempesta FW**, an open source *Application Delivery Controller*
- Open source alternative to **F5 BIG-IP** or **Fortinet ADC**
- “TLS CPS/TPS” is a common specification for network security appliances & ADCs



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Linux kernel TLS handshaks

- Very fast light-weight Linux kernel implementation
  - ...even for session resumption
  - there is modern research in the field
- Resistant against DDoS on TLS handshakes (asymmetric DDoS)
- Privileged address space for sensitive security data
  - Varnish: TLS is processed in separate process Hitch
    http://varnish-cache.org/docs/trunk/phk/ssl.html
  - Resistance against attacks like CloudBleed
    https://blog.cloudflare.com/incident-report-on-memory-leak-caused-by-cloudflare-parser-bug/

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Why NIST p256?

- ECDSA
  - RSA and NIST curves p256, p384, and p521 are the only allowed for CA certificates
    https://cabforum.org/baseline-requirements-documents/
  - P256 is the fastest NIST curve
  - P521 isn't recommended by IANA
    https://www.iana.org/assignments/tls-parameters/tls-parameters.xml#tls-parameters-8
  - RSA is slow and vulnerable to *asymmetric DDoS*
    https://vincent.bernat.im/en/blog/2011-ssl-dos-mitigation
- Curve25519
  - Much faster than NIST p256
  - In practice for ECDHE only

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TLS libraries performance issues

- Copies, memory initializations/erasing, memory comparisons
- `memcpy()`, `memset()`, `memcmp()` and their constant-time analogs
- Many dynamic allocations
- Large data structures
- Some math is outdated

12.79%	libc-2.24.so	_int_malloc
9.34%	nginx(openssl)	__ecp_nistz256_mul_montx
7.40%	nginx(openssl)	__ecp_nistz256_sqr_montx
3.54%	nginx(openssl)	sha256_block_data_order_avx2
2.87%	nginx(openssl)	ecp_nistz256_avx2_gather_w7
2.79%	libc-2.24.so	_int_free
2.49%	libc-2.24.so	malloc_consolidate
2.30%	nginx(openssl)	OPENSSL_cleanse
1.82%	libc-2.24.so	malloc
1.57%	[kernel.kallsyms]	do_syscall_64
1.45%	libc-2.24.so	free
1.32%	nginx(openssl)	ecp_nistz256_ord_sqr_montx
1.18%	nginx(openssl)	ecp_nistz256_point_doublex
1.12%	nginx(openssl)	__ecp_nistz256_sub_fromx
0.93%	libc-2.24.so	__memmove_avx_unaligned_erms
0.81%	nginx(openssl)	__ecp_nistz256_mul_by_2x
0.75%	libc-2.24.so	__memset_avx2_unaligned_erms
0.57%	nginx(openssl)	aesni_ecb_encrypt
0.54%	nginx(openssl)	ecp_nistz256_point_addx
0.54%	nginx(openssl)	EVP_MD_CTX_reset
0.50%	[kernel.kallsyms]	entry_SYSCALL_64

The source code

https://github.com/tempesta-tech/tempesta/tree/master/tls

- **Still in-progress**: we implement some of the algorithms on our own
- Initially the fork of **mbed TLS** 2.8.0 (*https://tls.mbed.org/*) - **x40 faster!**
  - very portable and easy to move into the kernel
  - cutting edge security
  - too many memory allocations (https://github.com/tempesta-tech/tempesta/issues/614)
  - big integer abstractions (*https://github.com/tempesta-tech/tempesta/issues/1064*)
  - inefficient algorithms, no architecture-specific implementations, ...
- We also take parts from **WolfSSL** (*https://github.com/wolfSSL/wolfssl/*)
  - very fast, but not portable
  - security *https://github.com/wolfSSL/wolfssl/issues/3184*

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ECDSA & ECDHE mathematics: Tempesta TLS, OpenSSL, WolfSSL

- OpenSSL 1.1.1h

```
256 bits ecdsa (nistp256)        36473 sign/s
256 bits ecdh (nistp256)         16620 op/s
```

- WolfSSL (current master)

```
ECDSA     256 sign               43260 ops/sec  (+19%)
ECDHE     256 agree              40878 ops/sec  (+146%)
```

- Tempesta TLS *(full TLS handshake operation)*

```
ECDSA sign (nistp256):   ops/s=38393
ECDHE srv (nistp256):    ops/s=13418
```

- *OpenSSL & WolfSSL don't include* ***ephemeral keys*** *generation (one more* `m * G` *operation)*

Demo!

- Tempesta TLS, Nginx-1.14.2/OpenSSL-1.1.1d, Nginx-1.17.8/WolfSSL
- TLS 1.2
  - full handshakes
  - abbreviated handshakes
- **`tls-perf`**
  https://github.com/tempesta-tech/tls-perf
  - establish & drop many TLS connections in parallel
  - like TLS-THC-DOS, but faster, more flexible, more options

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Data for proprietary vendors

- BIG-IP is only **30-50%** faster than Nginx/OpenSSL/DPDK
  https://www.youtube.com/watch?v=Plv87h8GtLc
- Avi Vantage (VMware) makes ~**2000** handshakes/second per 1CPU
  https://avinetworks.com/docs/latest/ssl-performance/

Why faster?

- No memory allocations in run time
- No context switches
- No copies on socket I/O
- Less message queues
- Zero-copy handshakes state machine
  https://netdevconf.info/0x12/session.html?kernel-tls-handhakes-for-https-ddos-mitigation
- **State of the art cryptography mathematics**

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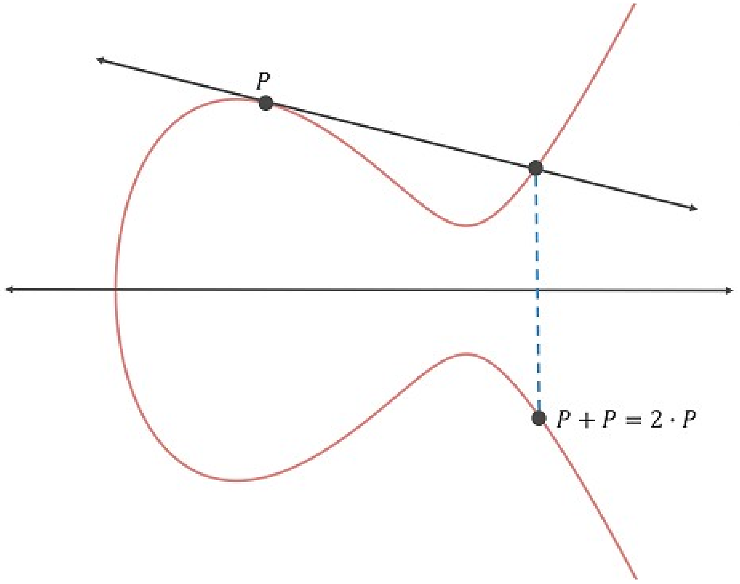
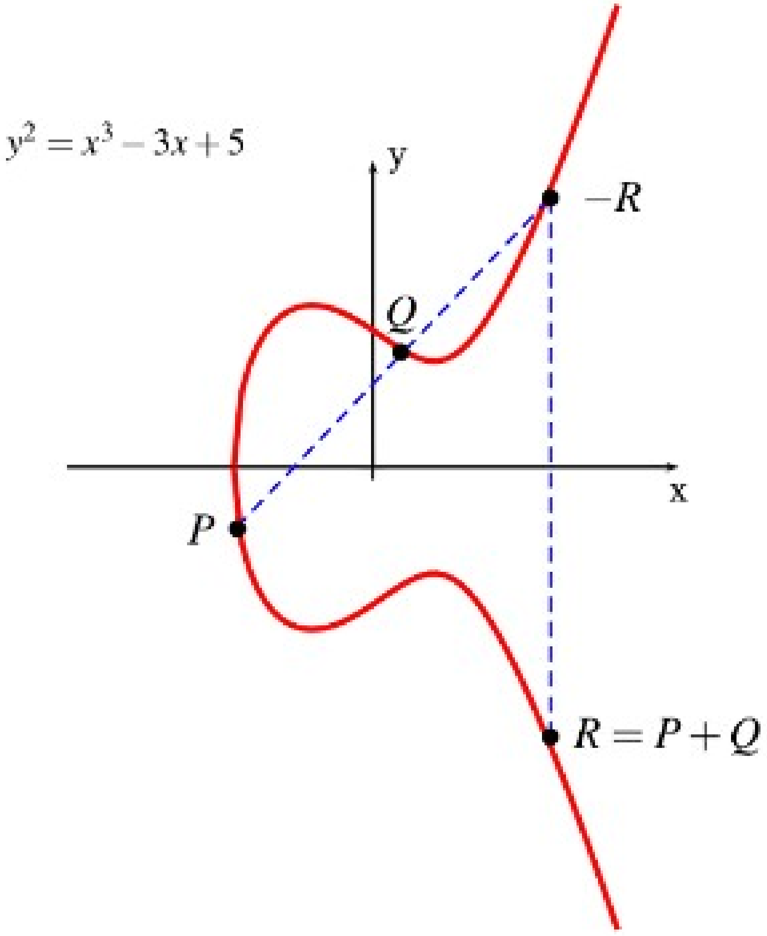
Elliptic curve cryptography

- Secp256r1: $y^2 = x^3 - 3x + b$ defined over the **field** GF(p)
  $p256 = 2^{256} - 2^{224} + 2^{192} + 2^{96} - 1$
- The group law
  - negatives: if P = (x, y), then -P = (x, -y)
  - addition: R = P + Q
  - doubling: R = P + P = 2*P





- **ECDSA**: k – secure random, G – **known** point
  k * G is used for the signature
- **ECDH**: d – private key, Q – public key
  shared secret: d * Q

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Point multiplication

OpenSSL: *“Fast prime field elliptic-curve cryptography with 256-bit primes"* by Gueron and Krasnov

- `Q = m * P` - the most expensive elliptic curve operation

```
for i in bits(m):
    Q ← point_double(Q)
    if m_i == 1:
        Q ← point_add(Q, P)
```

- Point multiplications in TLS handshake:
  - known point multiplication: precompute the table for doubled G
  - perfect forward secrecy ECDH**E**: generate keys G * d (d – random)
  - handshake: 2 known & 1 unknown point multiplications

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Point representation and coordinate systems

http://www.hyperelliptic.org/EFD/g1p/auto-shortw-jacobian.html

“Analysis and optimization of elliptic-curve single-scalar multiplication”, Bernstein & Lange, 2007

- *Jacobian* coordinates (rough estimations)
  - conversion overhead: `39*M + 4*S + 3*I` (for **`w`**(-indow) = **4**)
  - point addition (*mixed*) - `8*M + 3*S`, doubling - `2*M + 4*S`
- *Affine* coordinates (rough estimations)
  - point addition - `13*M + 4*S`, doubling - `4*M + 5*S`
- NIST 256 bits, `D = 256 / w = 64` Comb rounds (addition & doubling):

  `64 * (10*M + 7*S)` **<<** `64 * (17*M + 9*S)`

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Point addition

http://www.hyperelliptic.org/EFD/g1p/auto-shortw-jacobian.html#addition-add-2007-bl

- ex. addition in Jacobian coordinates (cost: 11M + 5S)
  $A = (x_1, y_1, z_1)$, $B = (x_2, y_2, z_2)$, then $C = A + B = (x_3, y_3, z_3)$ is

$$U_1 = X_1Z_2^2$$
$$U_2 = X_2Z_1^2$$
$$S_1 = Y_1Z_2^3$$
$$S_2 = Y_2Z_1^3$$
$$H = U_2 - U_1$$
$$R = S_2 - S_1$$
$$z_3 = HZ_1Z_2$$
$$x_3 = R^2 - H^3 - 2U_1H^2$$
$$y_3 = (U_1H^2 - X_3)R - S_1H^3$$

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The cost

- Modular multiplication (**`M`**) is the most expensive ***basic scalar*** operation
- Modular squaring (**`S`**) faster than M, usually **`0.8M`** (Montgomery)
  (0.9 for optimized FIPS due to more expensive modular reduction)
- Modular inversion (**I**) is very expensive, about **`100M`**

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Modular arithmetics

- ex. prime field F(29)

addition:	$17 + 20 = 8$	since	$37 \bmod 29 = 8$
subtraction:	$17 - 20 = 26$	since	$-3 \bmod 29 = 26$
multiplication:	$17 * 20 = 21$	since	$340 \bmod 29 = 21$
inversion:	$17^{-1} = 12$	since	$17 \cdot 12 \bmod 29 = 1$

- **Montgomery reduction** (the most used)
  - there is some overhead, but each modular operation is cheaper
- **FIPS reduction**
  - Can be faster if small number of modular operations is used
  - There are optimization techniques,
    e.g.“Low-Latency Elliptic Curve Scalar Multiplication” Bos, 2012
  - But still about 65% slower than Montgomery reduction

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Montgomery multiplication in P256

"Montgomery Multiplication", Henry S. Warren, Jr.

- Fast 256-bit integer multiplication with modular reduction on P256
- a, b < m (m - modulus P256)
- Set $n = 2^{256}$
- Transform multipliers to Montgomery domain (overhead):
  a' = an mod m b' = bn mod m
- Fast multiplication with reduction: `u = a'b'/n mod m`
  - compute only 256 bits of (`a'b' + (-m`$^{-1}$`a'b' mod n)m)/n`
  - if `u > m`, then `u ← u – m` (unconditionally, `carry` as a mask)
- Convert to ordinary number: $v = un^{-1} \bmod m$

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The math layers

- Different multiplication algorithms for fixed and unknown point
  - *”Efficient Fixed Base Exponentiation and Scalar Multiplication based on a Multiplicative Splitting Exponent Recoding”, Robert et al 2019*
- Point doubling and addition - everyone seems use the same algorithms
- Jacobian coordinates: different **modular inversion** algorithms
  - *“Fast constant-time gcd computation and modular inversion”, Bernstein et al, 2019*
- **Modular reduction** for scalar multiplications:
  - Montgomery has overhead vs FIPS speed: if we use less multiplcations it could make sense to use different reduction method FIPS *(seems deadend)*
  - *“Low-Latency Elliptic Curve Scalar Multiplication” Bos, 2012*

=> Balance between all the layers

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Example of math layers balancing

- For `w=5` we need **52** point additions for an unknown point multiplication
- Jacobian coordinates addition takes `11M + 5S`
- Affine-Jacobian coordinates addition takes `8M + 3S`
  - about `4.4M` cheaper if `S = 0.8M`
  - requires **2 coordinates normalizations** for Comba precomputation
  - coordinates normalization: 2^{w-1} `* (6M + 1S) + 1`**`I`**
- Almost the same for `S = 0.9M` and fast **inversion** `I < 100M`
- Montgomery arithmetics (`S = 0.8M`):
  - ECDHE +28% and ECDSA +6% performance

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Side channel attacks (SCA) resistance

- Timing attacks, simple power analysis, differential power analysis etc.
- Protections against SCAs:
  - Constant time algorithms
  - Dummy operations
  - Point randomization
  - *e.g. modular inversion **741 vs 266** iterations*
- **RDRAND** allows to write faster non-constant time algorithms
  - SRBDS mitigation costs about **97% performance**

    https://software.intel.com/security-software-guidance/insights/processors-affected-special-register-buffer-data-sampling?fbclid=IwAR1ifj3ZuAtNOabKkj3vFItBLSvOnMqlxH2I-QeN5KB-aji54J1BCJa9lLk

    https://www.phoronix.com/scan.php?page=news_item&px=RdRand-3-Percent&fbclid=IwAR2vmmR_LiroekUuw7KMRaHB7KThpqz0tIr1fX2GCW3HAvwt5Kb1p9xpLKo

Memory usage & SCA

- ex. ECDSA precomputed table for fixed point multiplication
  - mbed TLS: *~8KB* dynamically precomputed table, point randomization, constant-time algorithm, *full table scan*
  - OpenSSL: *~150KB static table, full scan*
  - *WolfSSL: ~150KB, direct index access (fixed in the new version)*
    https://github.com/wolfSSL/wolfssl/issues/3184

=> 150KB is far larger than L1d cache size, so many cache misses:

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Big Integers (aka MPIs)

“BigNum Math: Implementing Cryptographic Multiple Precision Arithmetic”, by Tom St Denis

- All the libraries use them (*not in hot paths*), mbed TLS **overuses** them
- `linux/lib/mpi/`, `linux/include/linux/mpi.h`

```
typedef unsigned long int mpi_limb_t;
struct gcry_mpi {
    int alloced;        /* array size (# of allocated limbs) */
    int nlimbs;         /* number of valid limbs */
    int nbits;          /* the real number of valid bits (info only) */
    int sign;           /* indicates a negative number */
    unsigned flags;
    mpi_limb_t *d;      /* array with the limbs */
};
```

- Need to manage variable-size integers
  => size-specific assembly implemetations

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Easy assembly

```
// a := a + b
// x[0] is the less significant limb,
// x[1] is the most significant limb.
void s_mp_add(unsigned long *a, unsigned long *b) {
    unsigned long carry;
    a[0] += b[0];
    carry = (a[0] < b[0]);
    a[1] += b[1] + carry;
}
```

```
// Pointer to a is in %RDI, pointer to b is in %RSI
movq    (%rdi), %r8
movq    8(%rdi), %r9

addq    (%rsi), %r8     // add with carry
addc    8(%rsi), %r9    // use the carry in the next addition

movq    (%r8), (%rdi)
movq    (%r9), 8(%rdi)
```

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Open questions and further research

- **Ice Lake** CPUs have negligeable downclocking on **AVX-512**
  https://travisdowns.github.io/blog/2020/08/19/icl-avx512-freq.html
- Parallel Montgomery computations
  J.W.Bos, "Montgomery Arithmetic from a Software Perspective", 2017
  - SIMD multiplications & squarings of two and more products
  - Interleaved Montgomery multiplications
- Better methods for point multiplications

Going to the Linux kernel upstream

- Details and the discussion
  - *https://netdevconf.info/0x14/session.html?talk-performance-study-of-kernel-TLS-handshakes*
  - *https://github.com/tempesta-tech/tempesta/issues/1433*
- Server-side only
- The full TLS handshake is in **softirq** (just like TCP)
- Fallback to a user-space TLS library on ClientHello
- Batches of handshakes in **1 FPU context**

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TODO

- More cryptography mathematics performance optimizations
  https://github.com/tempesta-tech/tempesta/issues/1064
  https://github.com/tempesta-tech/tempesta/issues/1335
- **TLS 1.3**
  https://github.com/tempesta-tech/tempesta/issues/1031
- Moving to the kernel asymmetric keys API
  https://github.com/tempesta-tech/tempesta/issues/1332
- The Linux kernel `/crypto` API performance issues
  - SHA-256 (crucial for TLS handshake) **30-100%** slower than OpenSSL
    https://github.com/tempesta-tech/tempesta/issues/1483
  - Extra copying and memory allocations in kTLS
    https://github.com/tempesta-tech/tempesta/issues/1064

Netdev papers about Tempesta TLS

- “Kernel HTTP/TCP/IP stack for HTTP DDoS mitigation”, Netdev 2.1, https://netdevconf.info/2.1/session.html?krizhanovsky
- “Kernel TLS handshakes for HTTPS DDoS mitigation”, Netdev 0x12, https://netdevconf.info/0x12/session.html?kernel-tls-handhakes-for-https-ddos-mitigation
- “Performance study of kernel TLS handshakes”, Netdev 014, https://netdevconf.info/0x14/session.html?talk-performance-study-of-kernel-TLS-handshakes

Thanks!

Contact us if you’re interested in fast Linux kernel TLS!

https://github.com/tempesta-tech/tempesta

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