Bar-Ilan Winter School
Lecture 5
Attacks and security notions for the SSH secure channel

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Overview

1. Introducing SSH
2. SSH measurement study
3. An unfortunate sequence of attacks on CBC-mode in OpenSSH
4. Security models for the SSH secure channel
5. Security analysis of other SSH and OpenSSH modes – CTR, ChaChaPoly, gEtM, AES-GCM
6. Better security for SSH: InterMAC

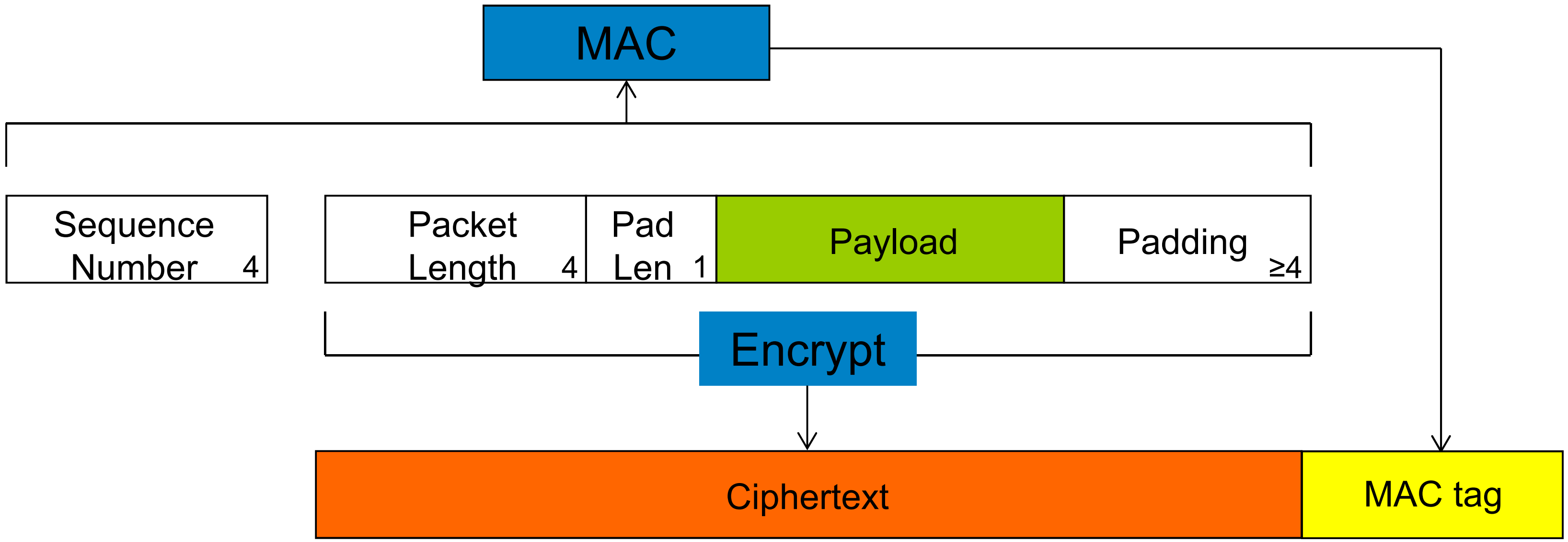
Introducing SSH and related work

Introduction to SSH

Secure Shell or SSH is a network protocol that allows data to be exchanged using a secure channel between two networked devices. Used primarily on Linux and Unix based systems to access shell accounts, SSH was designed as a replacement for TELNET and other insecure remote shells, which send information, notably passwords, in plaintext, leaving them open for interception. ***The encryption used by SSH provides confidentiality and integrity of data over an insecure network, such as the Internet****.*

– Wikipedia

SSH Binary Packet Protocol



- Stateful Encode-then-E&M construction
- Packet length field measures the size of the packet: |PadLen|+ |Payload| + |Padding|.
- RFC 4253 (2006): various block ciphers in **CBC mode (with chained IV)** and **RC4**.
- RFC 4344 (2006): added **CTR mode** for the corresponding block ciphers.

Timeline of related work on SSH BPP

2002.

- Formal security analysis of SSH BPP by Bellare, Kohno and Namprempre [BKN02]: introduce **stateful security notions for symmetric encryption** and proved **SSH-CTR** and **SSH-CBC variants** (w/o IV chaining) secure.

2009.

- Albrecht, Paterson and Watson [APW09] discover a plaintext-recovery attack against **SSH in CBC mode**.
- The attack exploits **fragmented delivery in TCP/IP**, and works on **all CBC variants** considered in [BKN02].
- The then leading implementation was OpenSSH (reported 80% of servers); OpenSSH team release a **patch** in version 5.2 to stop the specific attack.

Timeline of related work on SSH BPP

2010.

- The [APW09] attack highlights deficiencies in the [BKN02] security model.
- Paterson and Watson [PW10] prove SSH-CTR secure in an extended security model that allows adversary to deliver fragmented ciphertexts.

2012.

- Boldyreva, Degabriele, Paterson and Stam [BDPS12] study ciphertext fragmentation more generally, addressing limitations in the [PW10] model, introducing **IND-CFA security**.
- [BDPS12] also considers **boundary hiding** and resistance to a special type of **denial of service** attack as additional security requirements.

SSH measurement study

SSH measurement study

- In [ADHP16], we performed a measurement study of SSH deployment.
- We conducted two complete IPv4 address space scans in Nov/Dec 2015 and Jan 2016 using ZGrab/Zmap.
  - Grabbing banners and SSH servers' preferred algorithms.
  - Actual cipher used in a given SSH connection depends on client and server preferences.
- Roughly 2^{24} servers found in each scan.
- Nmap fingerprinting suggests mostly embedded routers and firewall devices.
- Data available at:

  https://bitbucket.org/malb/a-surfeit-of-ssh-cipher-suites/overview

SSH versions

software	scan 2015–12		scan 2016–01	
dropbear_2014.66	7,229,491	(42.0%)	8,334,758	(47.0%)
OpenSSH_5.3	2,108,738	(12.3%)	2,133,772	(12.0%)
OpenSSH_6.6.1p1	1,198,987	(7.0%)	1,124,914	(6.3%)
OpenSSH_6.0p1	554,295	(3.2%)	573,634	(3.2%)
OpenSSH_5.9p1	467,899	(2.7%)	500,975	(2.8%)
dropbear_2014.63	422,764	(2.5%)	197,353	(1.1%)
dropbear_0.51	403,923	(2.3%)	434,839	(2.5%)
dropbear_2011.54	383,575	(2.2%)	64,666	(0.4%)
ROSSSH	345,916	(2.0%)	333,992	(1.9%)
OpenSSH_6.6.1	338,787	(2.0%)	252,856	(1.4%)
dropbear_0.46	301,913	(1.8%)	335,425	(1.9%)
OpenSSH_5.5p1	262,367	(1.5%)	272,990	(1.5%)
OpenSSH_6.7p1	261,867	(1.5%)	213,843	(1.2%)
OpenSSH_6.2	255,088	(1.5%)	288,710	(1.6%)
dropbear_2013.58	236,409	(1.4%)	249,284	(1.4%)
dropbear_0.53	217,970	(1.3%)	213,670	(1.2%)
dropbear_0.52	132,668	(0.8%)	136,196	(0.8%)
OpenSSH	110,602	(0.6%)	108,520	(0.6%)
OpenSSH_5.8	88,258	(0.5%)	[illegible],144	[illegible]
OpenSSH_5.1	86,338	(0.5%)	44,[illegible]	[illegible]
OpenSSH_5.3p1	84,559	(0.5%)	0	[illegible]
OpenSSH_7.1	83,793	(0.5%)	0	[illegible]

Mostly OpenSSH and dropbear; others less than 5%.

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Dropbear at 56-58%. 886k older than version 0.52, so vulnerable to variant of 2009 CBC-mode attack.

The state of SSH today: SSH versions

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OpenSSH at 37-39%.
166k older than version 5.2 and prefer CBC mode, so vulnerable to 2009 attack.

SSH versions

- Dropbear dominates over OpenSSH.
- Long tail of old software versions.
    - Most popular version of OpenSSH was version 5.3, released Oct 2009 (current version is 7.5).
    - Determined by major Linux distros?
- Non-negligible percentage of Dropbear and OpenSSH servers were potentially still vulnerable to the 2009 attack.
    - 8.4% for Dropbear.

OpenSSH preferred algorithms

encryption and mac algorithm	count	
aes128-ctr + hmac-md5	3,877,790	(57.65%)
aes128-ctr + hmac-md5-etm@	2,010,936	(29.90%)
aes128-ctr + umac-64-etm@	331,014	(4.92%)
aes128-cbc + hmac-md5	161,624	(2.40%)
chacha20-poly1305@	115,526	(1.72%)
aes128-ctr + hmac-sha1	68,027	(1.01%)
des + hmac-md5	40,418	(0.60%)
aes256-gcm@	28,019	(0.42%)
aes256-ctr + hmac-sha2-512	17,897	(0.27%)
aes128-cbc + hmac-sha1	11,082	(0.16%)
aes128-ctr + hmac-ripemd160	10,621	(0.16%)

OpenSSH preferred algorithms ("@" = "@openssh.com")

- Lots of diversity (155 different combinations).
- CTR dominates, followed by CBC, surprising amount of EtM.
- ChaCha20-Poly1305 on the rise? (became default in OpenSSH 6.9).
- Small amount of GCM.

Dropbear preferred algorithms

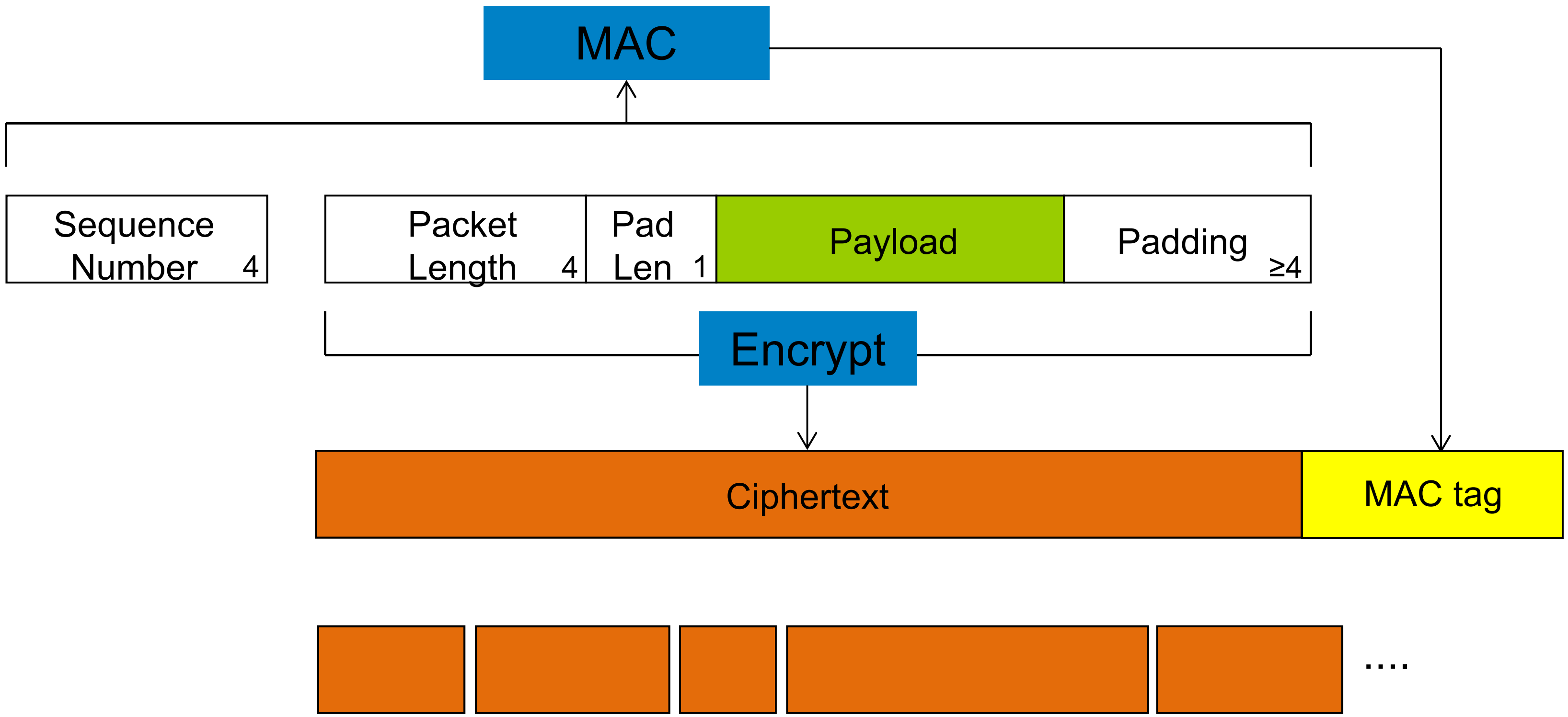
encryption and mac algorithm	count	
aes128-ctr + hmac-sha1-96	8,724,863	(90.44%)
aes128-cbc + hmac-sha1-96	478,181	(4.96%)
3des-cbc + hmac-sha1	321,492	(3.33%)
aes128-ctr + hmac-sha1	62,465	(0.65%)
aes128-ctr + hmac-sha2-256	36,150	(0.37%)
aes128-cbc + hmac-sha1	14,477	(0.15%)

Dropbear preferred algorithms

- Less diversity than OpenSSH.
- CTR also dominates, followed by CBC.
- No "exotic" options.
- All CBC modes unpatched against variant of 2009 attack (8.4%).

An unfortunate sequence of attacks on CBC mode in OpenSSH

SSH Binary Packet Protocol

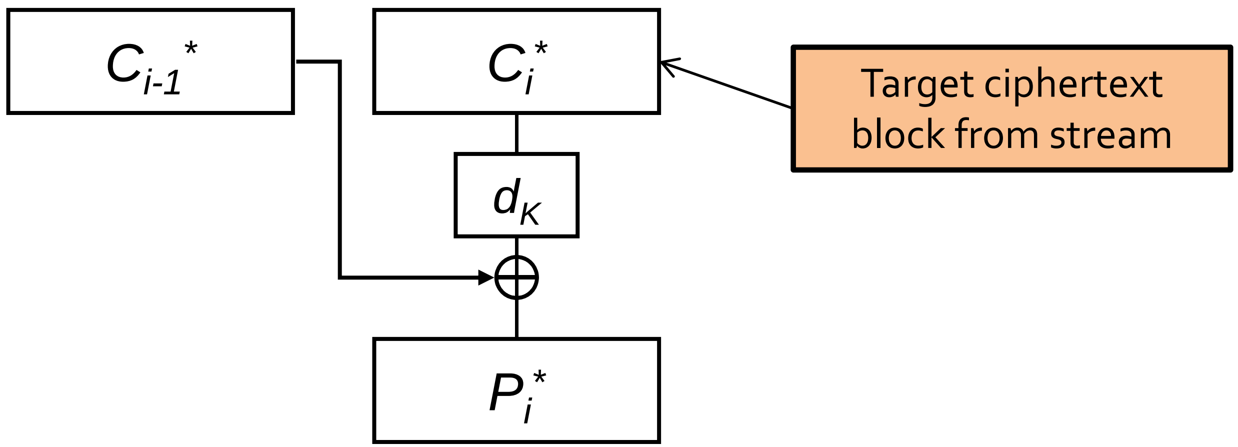


How would you perform decryption for an incoming sequence of ciphertext fragments?

The [APW09] attack (simplified)

- Decryption in OpenSSH CBC mode (prior to 5.2):
  - Use a buffer to hold the incoming sequence of ciphertext fragments.
  - Decrypt the fragments block-by-block as they arrive.
  - 4-byte packet length field LF is obtained from the **first** block of the **first** fragment to be received.
  - Continue to buffer+decrypt until a total of LF+|MAC| bytes have been received.
  - Verify the MAC on SQN || PTXT (with connection termination and error message if MAC verification fails).

Breaking CBC mode in SSH [APW09]



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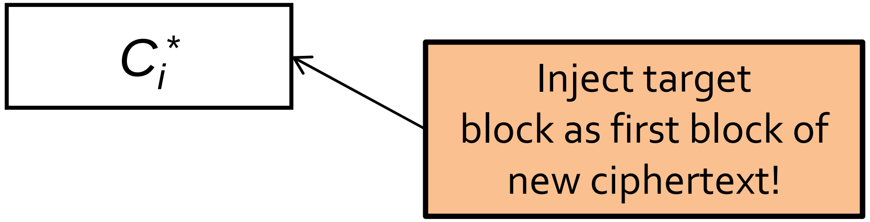

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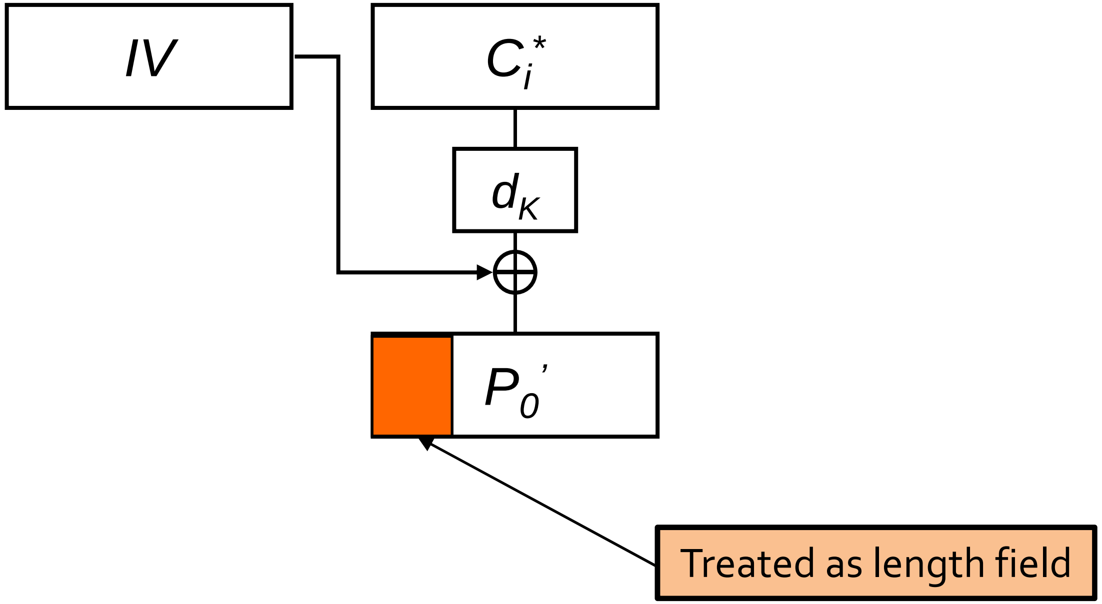

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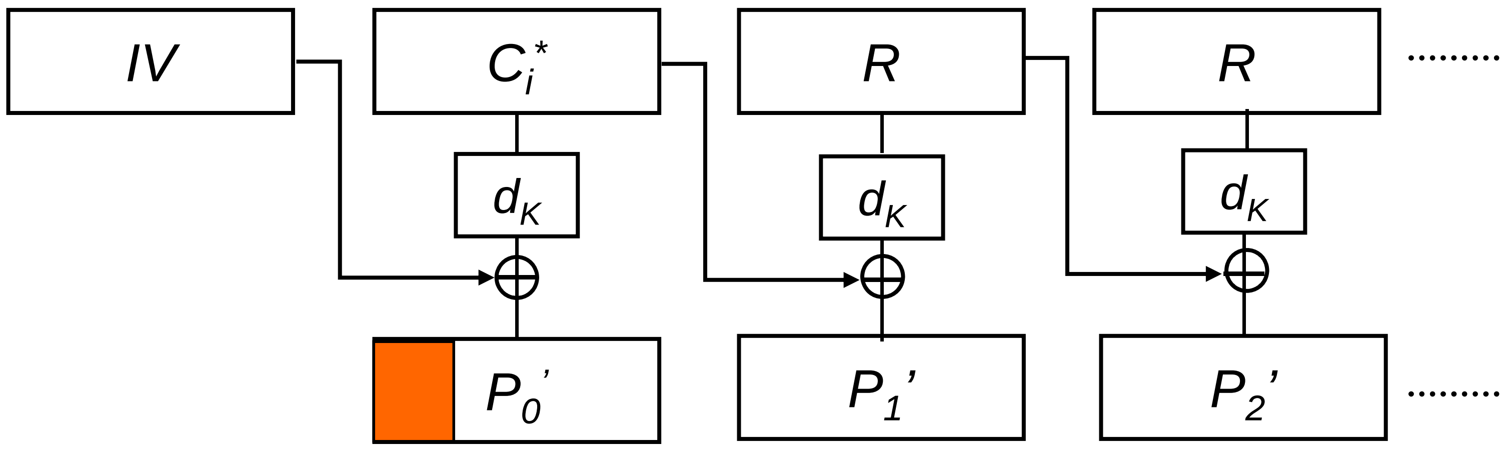

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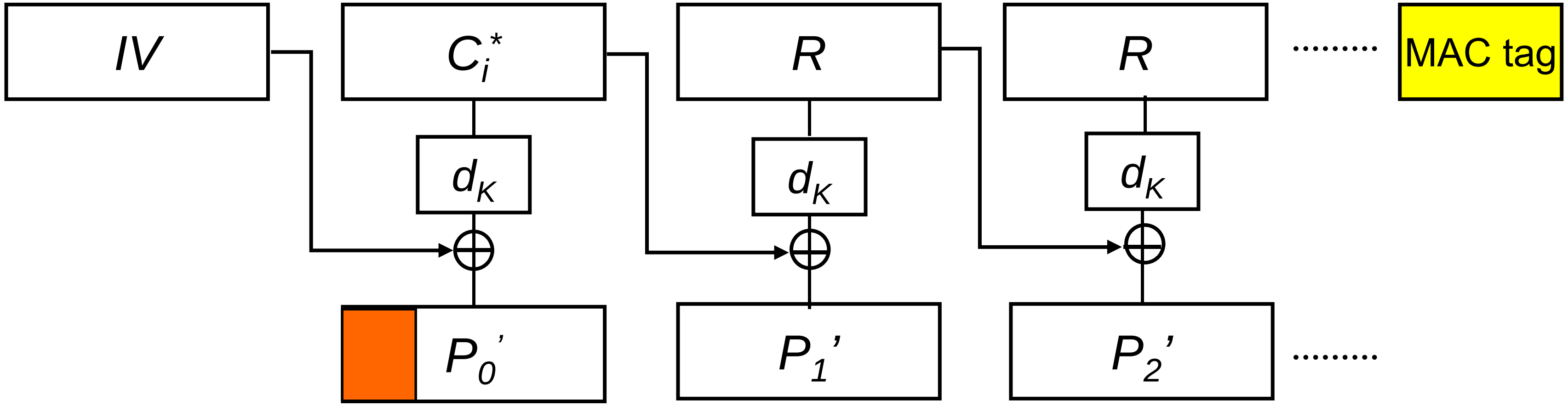
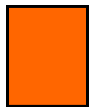
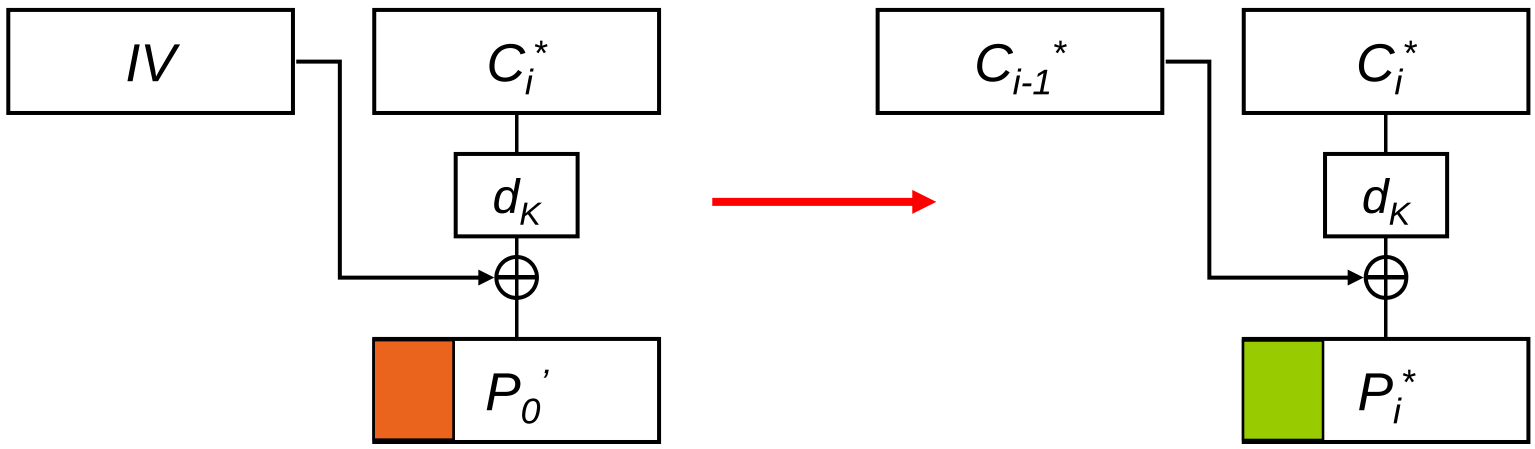


- Once **enough** data has arrived, the receiver will get what it thinks is the MAC tag
  - The MAC verification will fail with overwhelming probability
  - So the connection is terminated (with an error message)
- **Question**: How much data is "enough" so that the receiver decides to check the MAC?
- Answer: whatever is specified in the length field: 

Breaking CBC mode in SSH [APW09]



- Knowing IV and 32 bits of P_0', the attacker can now recover 32 bits of the target plaintext block P_i^*.

$$\text{LF} \oplus [IV]_{0..3} = \square \oplus [C_{i-1}^{*}]_{0..3}$$

The [APW09] attack (less simplified)

- OpenSSH5.1 actually performs two sanity checks on the length field when decrypting the first ciphertext block:
  - Check 1: $5 \leq LF \leq 2^{18}$.
  - Check 2: total length ($LF+4$) is a multiple of the block size:

$$LF + 4 \bmod BL = 0.$$

- Each check produces a *different* error message on the network, distinguishable by attacker.
- If both checks pass, then OpenSSH waits for more bytes, then performs MAC check, resulting in a third distinct error message.
- The different error messages allow up to 32 bits of plaintext to be recovered with probability 2^{-18}.

OpenSSH 5.2 patch against [APW09] attack

Sanity checks:

$5 \leq LF \leq 2^{18}$

$LF + 4 \bmod BL = 0$

→ FAIL → ~~*ssh2_msg_disconnect*~~

→ Wait until 2^{18} bytes have arrived, then check a MAC on 2^{18} bytes.

↓

PASS

↓

Wait for LF+|MAC| bytes

↓

VERIFY → FAIL → ~~*"corrupted MAC on input"*~~

→ Wait until 2^{18} bytes have arrived, then check a MAC on 2^{18} bytes.

No error message is sent until 2^{18} bytes of ciphertext have arrived.

Is this a good patch?

OpenSSH 5.2 patch against [APW09] attack

Sanity checks:

$5 \leq LF \leq 2^{18}$ → FAIL → ~~*ssh2_msg_disconnect*~~

$LF + 4 \bmod BL = 0$

→ Wait until 2^{18} bytes have arrived, then check a MAC on 2^{18} bytes.

↓

PASS

↓

Wait for LF+|MAC| bytes

MAC on 2^{18} bytes

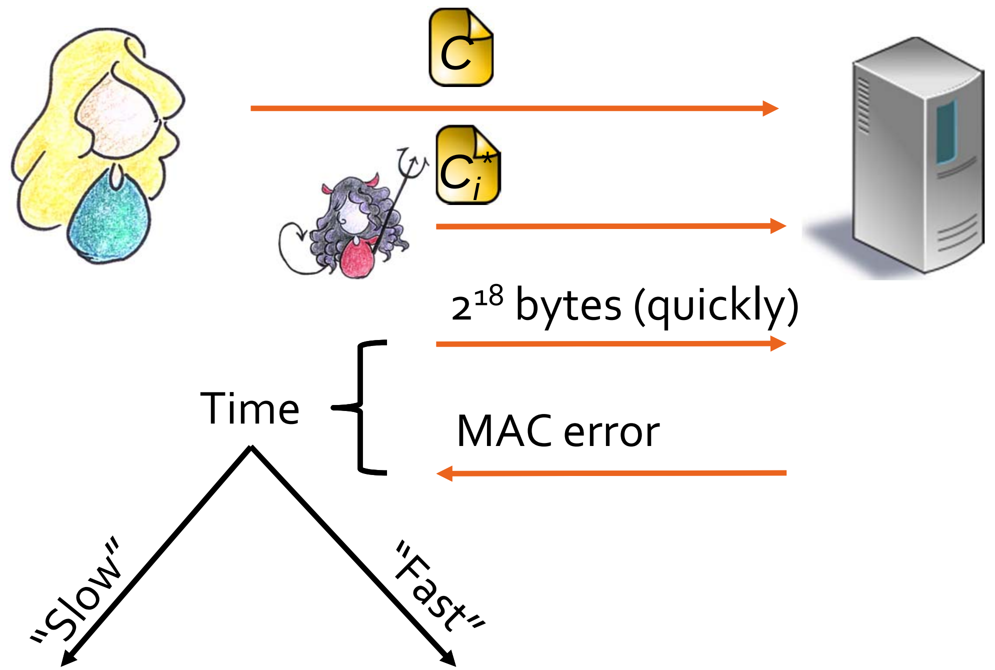
↓

VERIFY → FAIL → ~~*"corrupted MAC on input"*~~

MAC on ~LF bytes + MAC on 2^{18} bytes → Wait until 2^{18} bytes have arrived, then check a MAC on 2^{18} bytes.

No error message is sent until 2^{18} bytes of ciphertext have arrived.

[ADHP16] attack against the OpenSSH 5.2 patch



MAC on ~LF bytes +
MAC on 2^{18} bytes
Sanity check PASS

MAC on 2^{18} bytes
Sanity check FAIL

- Attacker can distinguish PASS/FAIL conditions, leaking 18 bits of plaintext.
- With careful timing, attacker can recover ~30 bits of plaintext.

OpenSSH 7.3 patch against [ADHP16] attack

Sanity checks: $5 \leq LF \leq 2^{18}$, $LF + 4 \bmod BL = 0$ → FAIL → ~~*ssh2_msg_disconnect*~~

→ Wait until 2^{18} bytes have arrived, then check a MAC on 2^{18} bytes.

MAC on 2^{18} bytes

↓

PASS

↓

Wait for LF+|MAC| bytes

↓

VERIFY → FAIL → ~~*"corrupted MAC on input"*~~

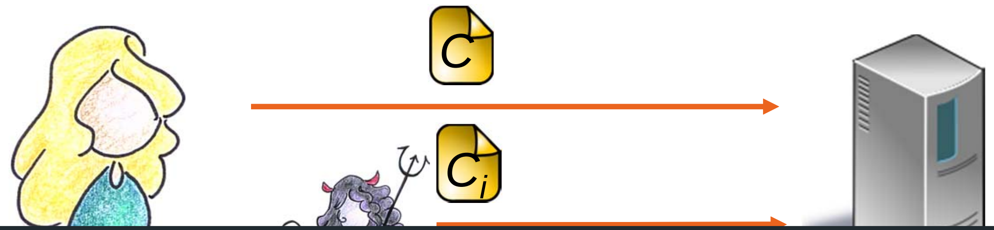
MAC on ~LF bytes +
MAC on 2^{18} - LF bytes

→ ~~Wait until 2^{18} bytes have arrived, then check a MAC on 2^{18} bytes.~~

→ Wait until 2^{18} bytes have arrived, then check a MAC on 2^{18} - LF bytes.

So is this a good patch?

Attacking the OpenSSH 7.3 patched patch



Our recommended patch actually made things significantly worse!

Performed

"Slow"

"Fast"

MAC on ~LF bytes +
MAC on 2^18 - LF bytes
Sanity check PASS

MAC on 2^18 bytes
Sanity check FAIL

Timing difference


I wonder if anyone noticed?
I'm not so sure!
I think we got away with it!
BEST PAPER AWARD
BEST PAPER AWARD

Disclosure of the attacks

- We first notified the OpenSSH team of the attack on the patch for the [APW09] attack on 5/5/2016.
- They first set of countermeasures in OpenSSH 7.3 (released 1/8/2016).
- We then notified OpenSSH of the new attack on 15/12/2016, along with some other, more subtle byte counting issues.
- These were partly addressed in OpenSSH 7.5 (released 20/3/2017).
- But several residual issues remain unpatched, **including the final attack**.
- In defence of OpenSSH:
  - OpenSSH has steadily been deprecating old algorithms and modes.
  - For example, CBC mode was already disabled by default in OpenSSH 6.7.

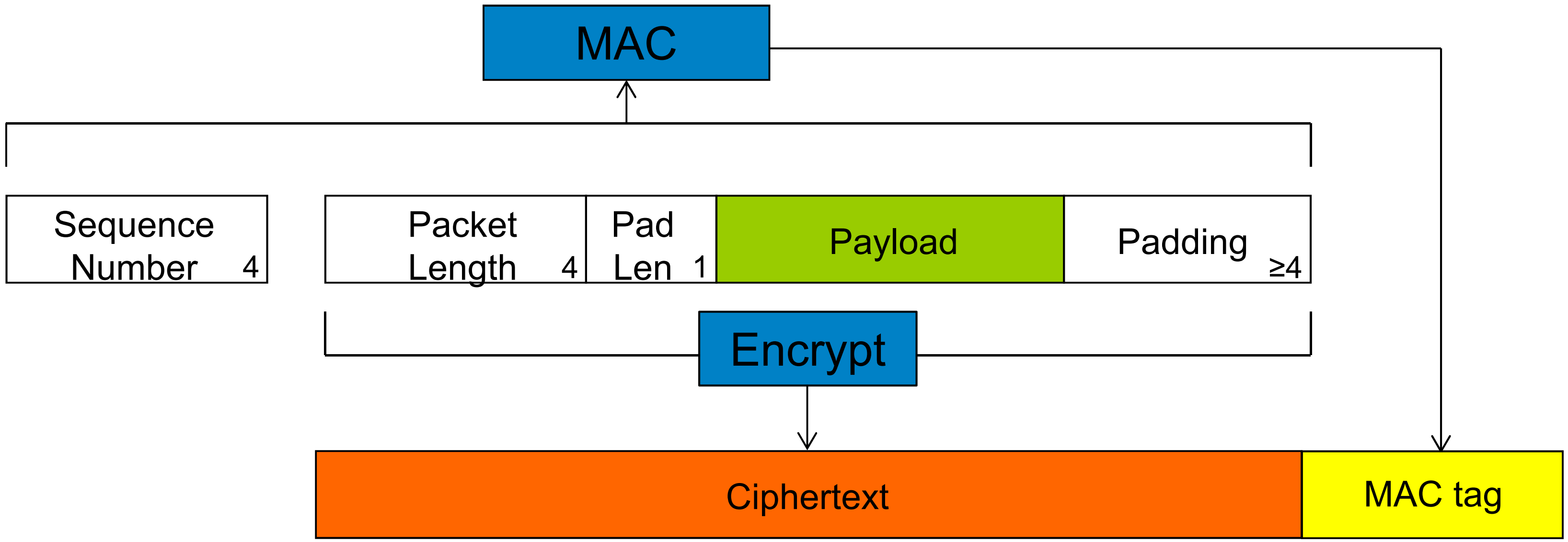
Security analysis of other SSH and OpenSSH modes – CTR, gEtM, AES-GCM, ChaCha20Poly1305

OpenSSH encryption modes

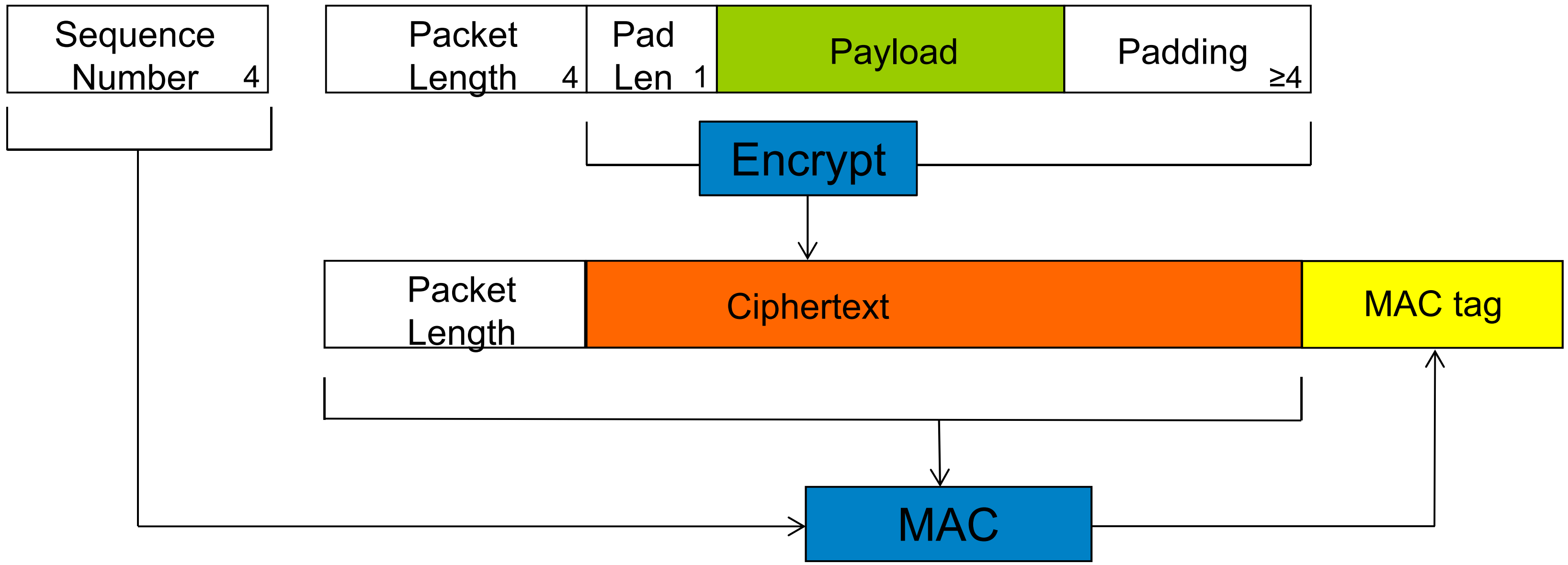
A number of new schemes have been introduced in OpenSSH since [APW09]:

- AES-GCM: since v6.2; **length field not encrypted** but is instead treated as associated data.
- generic Encrypt-then-MAC (gEtM): since v6.2; overrides native E&M processing; **length field not encrypted** but protected by MAC.
- ChaCha20-Poly1305@openssh.com: since v6.5 and promoted to default in v6.9; **reintroduces encryption of length field**.

Binary Packet Protocol native E&M construction



Binary Packet Protocol generic EtM construction



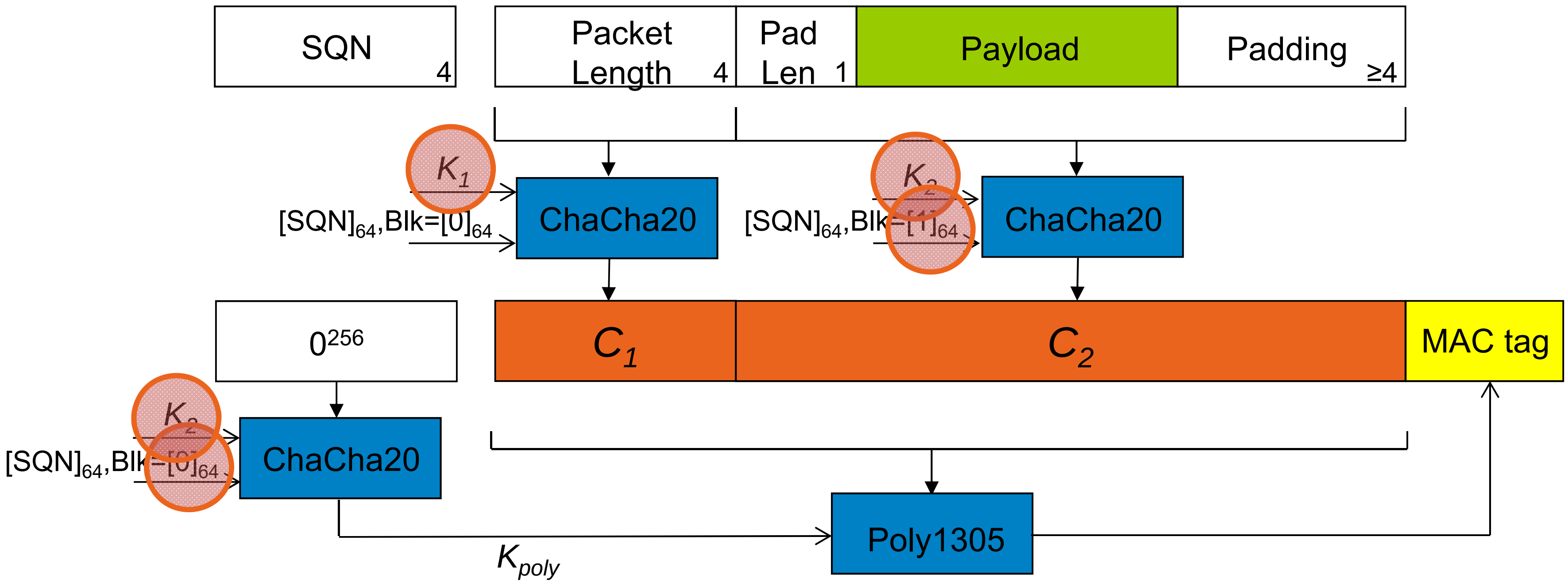
- Stateful Encode-then-EtM construction.
- AES-GCM works similarly.
- Note packet length field in the clear: construction gives up on hiding packet lengths.
- Code = documentation.

Binary Packet Protocol generic EtM security issue

```
/* EtM: compute mac over encrypted input */
if (mac && mac->enabled && mac->etm) {
    if ((r = mac_compute(mac, state->p_read.seqnr, ...
}
if ((r = sshbuf_reserve(state->incoming_packet, aadlen + need, ...
if ((r = cipher_crypt(&state->receive_context, state->p_read.seqnr, cp, ...
if ((r = sshbuf_consume(state->input, aadlen + need + authlen)) != 0)
    goto out;
/*
 * compute MAC over seqnr and packet,
 * increment sequence number for incoming packet
 */
if (mac && mac->enabled) {
    if (!mac->etm) ...
    if (timingsafe_bcmp(macbuf, sshbuf_ptr(state->input), ...
    }
```

- Sequence: compute MAC, then decrypt, then check MAC.
- Issue arises because of retrofitting gEtM in legacy E&M code.
- No concrete attack, but dangerous to decrypt unauthenticated ciphertext (cf. padding oracle attacks).
- Addressed in OpenSSH 7.3.

ChaCha20-Poly1305@openssh.com



- ChaCha20-Poly1305@openssh.com: since OpenSSH 6.5 and promoted to default in v6.9; **reintroduces encryption of length field**.
- OpenSSH developers seem to care a lot about **hiding packet lengths!**

Security analysis from [ADHP16]

- We used the **framework of [BDPS12]** for **symmetric encryption schemes supporting ciphertext fragmentation** to analyse the security of these schemes.
- We identified and fixed a **technical issue** in the IND-sfCFA confidentiality definition from [BDPS12].
- We introduced a matching notion of **ciphertext integrity**, INT-sfCTXT, which was not considered in [BDPS12].

Symmetric Schemes supporting ciphertext fragmentation: A flavour of the formal definitions

- [BDPS12] introduced a class of symmetric encryption (SE) schemes supporting ciphertext fragmentation.
- **KGen:** selects key K and sets initial encryption and decryption states σ_0, τ_0.
- **Enc:** takes complete plaintext and state as input and produces corresponding ciphertext and an updated state:

$$(c,\sigma') \leftarrow \text{Enc}(K,m,\sigma)$$

- **Dec:** takes arbitrary bit-strings (and state) as input, and produces bit-strings from $(\{0,1\}^* \cup \{\mathbf{P}\} \cup S_{err})^* \times \Sigma$
  - S_{err} : set of possible error symbols arising during decryption.
  - **P**: a distinguished "end of message" symbol.
  - Σ: state space of decryption algorithm.

Correctness for SE schemes supporting fragmentation

- Informally: “Decryption works properly across fragmented and concatenated ciphertexts”.
- Formally, for any sequence of calls to Enc:

$$(c_i, \sigma_i) \leftarrow \mathrm{Enc}(K, m_i, \sigma_{i-1}) \quad (\text{for } i=1,\ldots,t)$$

and any sequence of ciphertext fragments:

$$f_1, f_2, \ldots, f_n,$$

if $c_1 \| c_2 \| \ldots \| c_t$ is a prefix of $f_1 \| f_2 \| \ldots \| f_n$, and

$$(m'_i, \tau_i) \leftarrow \mathrm{Dec}(K, f_i, \tau_{i-1}) \quad (\text{for } i=1,\ldots,n)$$

then

$$m_1 \mathbf{P} m_2 \mathbf{P} \ldots m_3 \mathbf{P} \text{ is a prefix of } m'_1 \| m'_2 \| \ldots \| m'_n.$$

(NB other subtly different correctness definitions are possible!)

Security for SE schemes supporting ciphertext fragmentation

- Confidentiality and integrity notions extend those of [BKN02] for stateful setting.
- INDsf-CFA: indistinguishability of encryptions under a stateful, chosen fragment attack.
- Adversary has a regular encryption oracle, called on equal-length message pairs (m_0,m_1).
- Adversary has a decryption oracle accepting a sequence of fragments $f_1, f_2, \ldots$ as input.
- Decryption oracle suppresses output until sequence ‘goes out of sync’ with output of encryption oracle.

Security for SE schemes supporting ciphertext fragmentation [ADHP16]

alg. INI

sync $\leftarrow$ true
$i \leftarrow 0, j \leftarrow 0$
$C \leftarrow [\,], M \leftarrow [\,]$
$F \leftarrow \varepsilon, M' \leftarrow \varepsilon$
$b \twoheadleftarrow \{0, 1\}$
$(K, \sigma, \varrho) \leftarrow \mathcal{K}$
return

alg. LR(b, m_0, m_1)

if $|m_0| \neq |m_1|$ **return** ε
$(c, \sigma) \leftarrow \mathcal{E}_K(m_b, \sigma)$
$i \leftarrow i + 1, C[i] \leftarrow c$
$M[i] \leftarrow m_b \parallel \P$
return c

alg. ENC(m)

$(c, \sigma) \leftarrow \mathcal{E}_K(m, \sigma)$
$i \leftarrow i + 1, C[i] \leftarrow c$
$M[i] \leftarrow m \parallel \P$
return c

alg. DEC(f)

$(m, \varrho) \leftarrow \mathcal{D}_K(f, \varrho)$
$F \leftarrow F \parallel f, M' \leftarrow M' \parallel m$
if sync $=$ true
  $j \leftarrow \min(\{n \mid C[1 \ldots n] \not\preceq F\} \cup \{i\})$
  if $F \preceq C[1 \ldots j]$
    $m \leftarrow \varepsilon$
  else
    $m \leftarrow M' \,\%\, M[1 \ldots j-1]$
    if $C[1 \ldots j] \preceq F$
      $m \leftarrow M' \,\%\, M[1 \ldots j]$
    if $m \neq \varepsilon$
      sync $\leftarrow$ false
return m

Security analysis from [ADHP16]

	IND-sfCFA	INT-sfCTF	BH-CPA	BH-sfCFA	n-DOS-sfCFA
CBC	✗	✓	✓	✗	✗
fixed-CBC	✗	✓	✓	✗	✗
CTR	✓	✓	✓	✗	✗
fgEtM	✓	✓	✗	✗	✗
AES-GCM	✓	✓	✗	✗	✗
ChaCha20-Poly1305	✓	✓	✓	✗	✗

Security comparison of SSH AE modes

Additional goals from [BDPS12]:

- BH-CPA (passive adversary) – boundary hiding for passive attackers.
- BH-sfCFA (active adversary) – boundary hiding for active attackers.
- *n*-DOS-sfCFA: decryption must produce some output (plaintext or error) after receiving at most an *n*-bit sequence of fragments chosen by adversary.

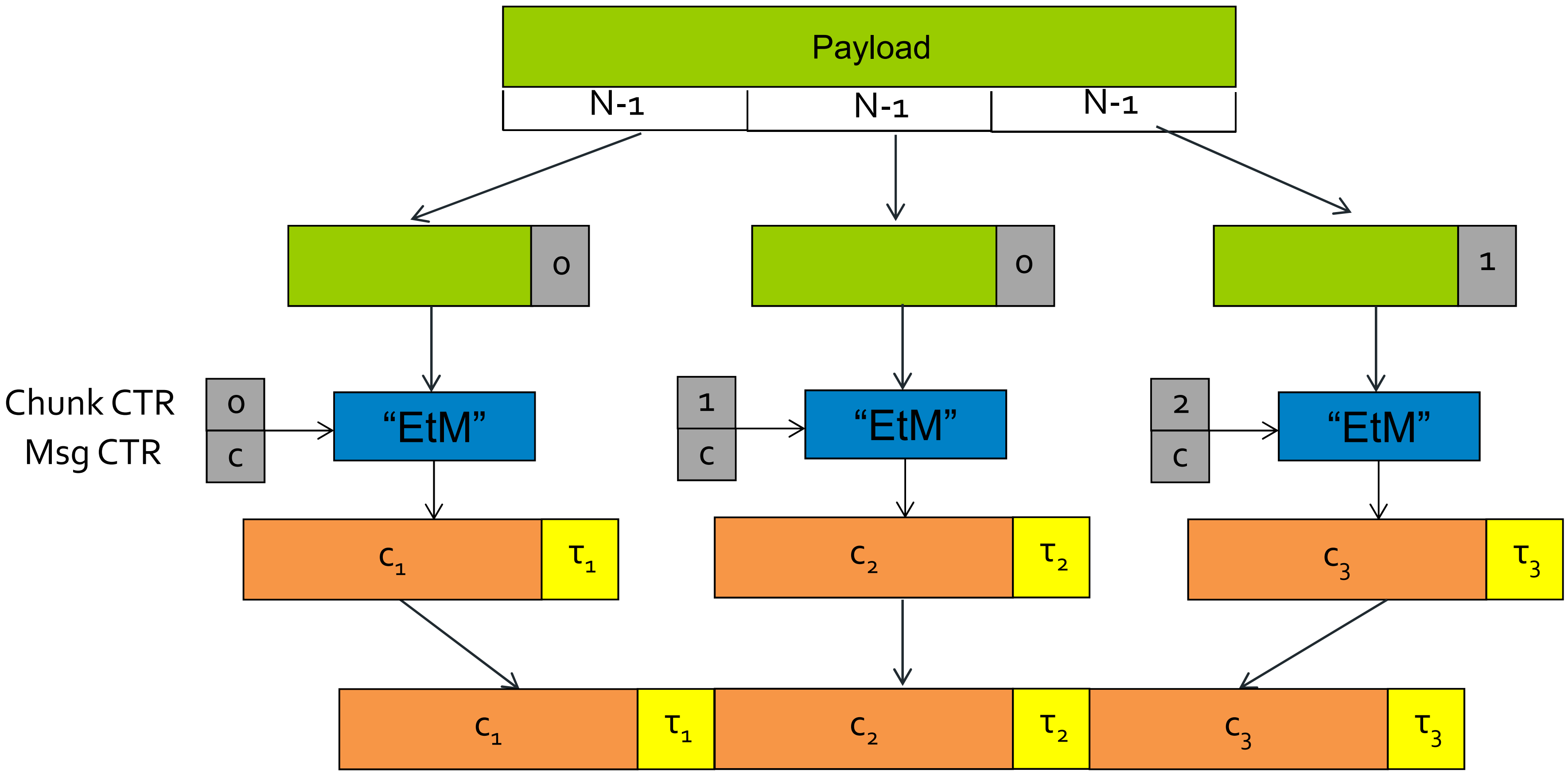
InterMAC

InterMAC

- An encryption scheme proposed in [BDPS12].
- Parameterised by a positive integer N (the **chunk length**).
- Satisfies all 5 security notions:

  IND-sfCFA, IND-sfCTF, BH-CPA, BH-sfCFA, (N + |MAC|)-DOS-sfCFA.
- Applies a generic EtM construction to chunks of data, incorporating additional metadata in the MAC computation.
- Simple, easy to analyse construction; advanced security properties are intuitively obvious.
- Small N: good DoS protection, but larger bandwidth overhead.
- **Idea**: refine and implement InterMAC in OpenSSH to obtain stronger security than is currently available.

InterMAC



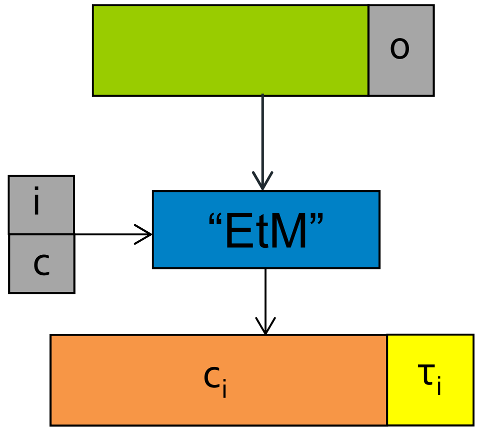
Payload
N-1
N-1
N-1
0
0
1
Chunk CTR
Msg CTR
0
c
"EtM"
1
c
"EtM"
2
c
"EtM"
c1
τ1
c2
τ2
c3
τ3
c1
τ1
c2
τ2
c3
τ3

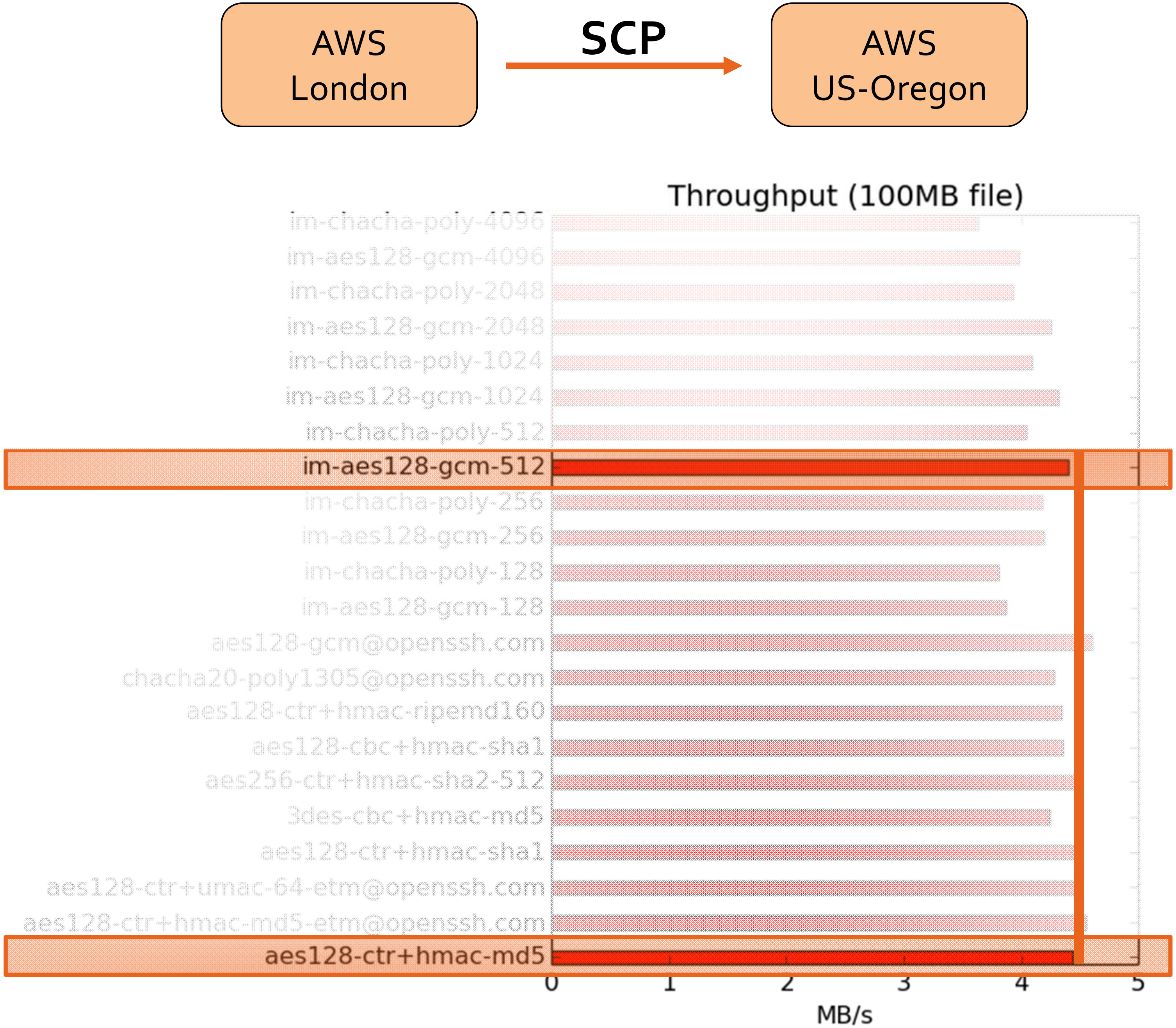
InterMAC: From Theory to Practice

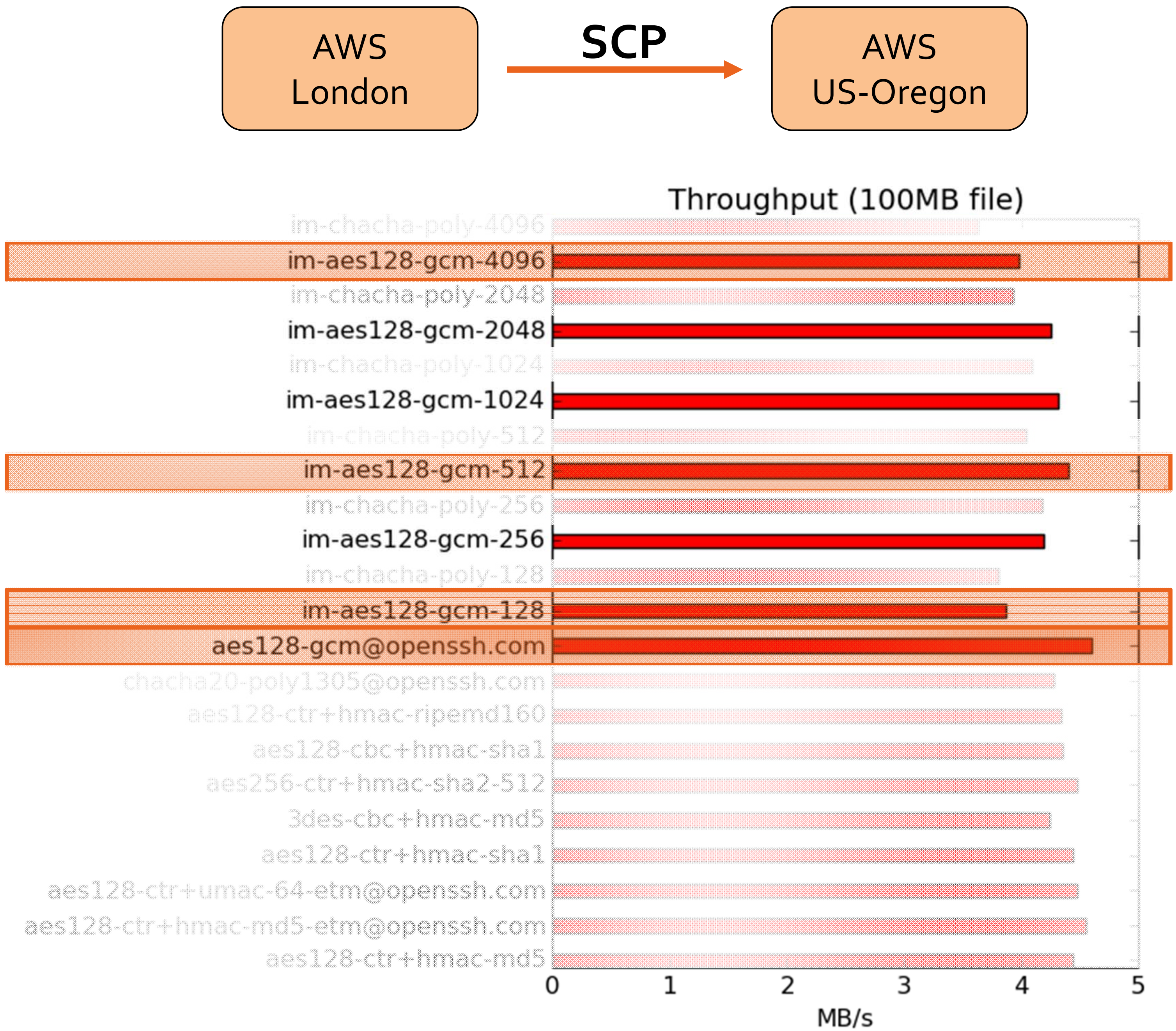
- Use byte-oriented rather than bit-oriented format.
- Abandon underlying SSH packet format (so no length field, no padding byte, no random padding).
- Need some kind of plaintext padding (length not usually a multiple of N-1!): variant of ABYTE padding.
- Replace EtM with nonce-based AEAD, e.g. AES-GCM or ChaCha20-Poly1305.
- Chunk and message counter then become Associated Data, or are used to construct the nonce.
  - We choose the latter.

InterMAClib and OpenSSH

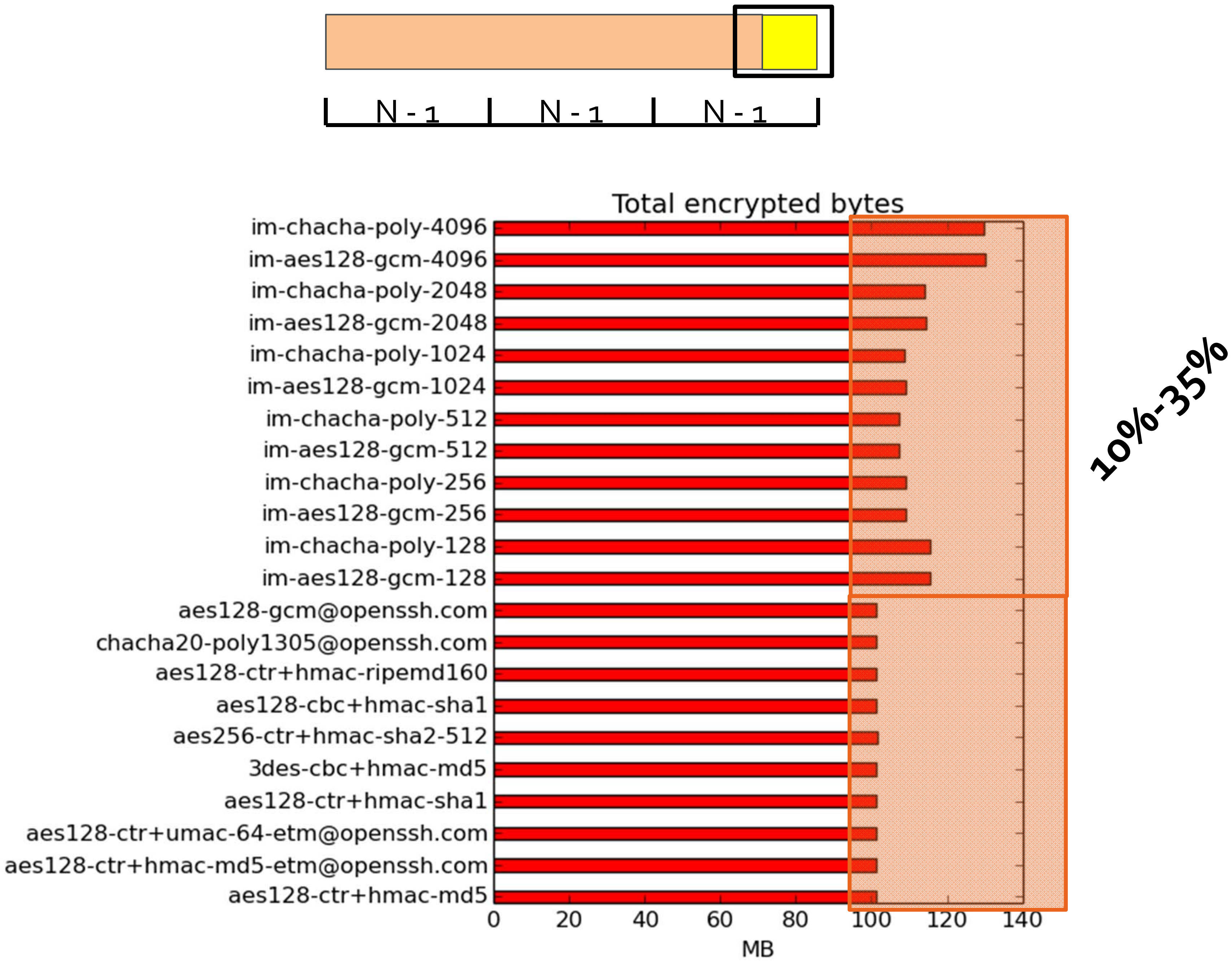
- C-implementation of InterMAC.
- Aim is to make the library easy to use for a developer.
- API: **im_initialise, im_encrypt, im_decrypt**.
- Message counter and nonce management done by the library.
- Currently supports ChaCha-Poly and AES-GCM.
- Easy to extend with other AEAD schemes.
- POC integration into OpenSSH (v7.4).
- SSH InterMAC cipher suites: **im-aes128-gcm-N, im-chacha-poly-N**.




AWS
London
SCP
AWS
US-Oregon
Throughput (100MB file)
im-chacha-poly-4096
im-aes128-gcm-4096
im-chacha-poly-2048
im-aes128-gcm-2048
im-chacha-poly-1024
im-aes128-gcm-1024
im-chacha-poly-512
im-aes128-gcm-512
im-chacha-poly-256
im-aes128-gcm-256
im-chacha-poly-128
im-aes128-gcm-128
aes128-gcm@openssh.com
chacha20-poly1305@openssh.com
aes128-ctr+hmac-ripemd160
aes128-cbc+hmac-sha1
aes256-ctr+hmac-sha2-512
3des-cbc+hmac-md5
aes128-ctr+hmac-sha1
aes128-ctr+umac-64-etm@openssh.com
aes128-ctr+hmac-md5-etm@openssh.com
aes128-ctr+hmac-md5
0
1
2
3
4
5
MB/s



AWS
London
SCP
AWS
US-Oregon
Throughput (100MB file)
im-chacha-poly-4096
im-aes128-gcm-4096
im-chacha-poly-2048
im-aes128-gcm-2048
im-chacha-poly-1024
im-aes128-gcm-1024
im-chacha-poly-512
im-aes128-gcm-512
im-chacha-poly-256
im-aes128-gcm-256
im-chacha-poly-128
im-aes128-gcm-128
aes128-gcm@openssh.com
chacha20-poly1305@openssh.com
aes128-ctr+hmac-ripemd160
aes128-cbc+hmac-sha1
aes256-ctr+hmac-sha2-512
3des-cbc+hmac-md5
aes128-ctr+hmac-sha1
aes128-ctr+umac-64-etm@openssh.com
aes128-ctr+hmac-md5-etm@openssh.com
aes128-ctr+hmac-md5
0
1
2
3
4
5
MB/s



N - 1
N - 1
N - 1
Total encrypted bytes
im-chacha-poly-4096
im-aes128-gcm-4096
im-chacha-poly-2048
im-aes128-gcm-2048
im-chacha-poly-1024
im-aes128-gcm-1024
im-chacha-poly-512
im-aes128-gcm-512
im-chacha-poly-256
im-aes128-gcm-256
im-chacha-poly-128
im-aes128-gcm-128
aes128-gcm@openssh.com
chacha20-poly1305@openssh.com
aes128-ctr+hmac-ripemd160
aes128-cbc+hmac-sha1
aes256-ctr+hmac-sha2-512
3des-cbc+hmac-md5
aes128-ctr+hmac-sha1
aes128-ctr+umac-64-etm@openssh.com
aes128-ctr+hmac-md5-etm@openssh.com
aes128-ctr+hmac-md5
0
20
40
60
80
100
120
140
MB
10%-35%

Concluding Remarks

Concluding Remarks

- We have developed a deeper understanding of the diverse set of encryption modes available in (Open)SSH.
    - Measurement study, new attacks on CBC mode, security analysis
- Formal modelling of security for the goals targeted by SSH.
- None of the schemes in use possesses all the security properties desirable for SSH.
    - Boundary-hiding and DoS-resistance not achieved.
- Yet such schemes do exist, e.g. InterMAC from [BDPS12].
- In our current work, we are developing and prototyping efficient, provably secure alternatives that have all the desired properties.