

Advanced security notions for the SSH secure channel: theory and practice

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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 analysis of other SSH and OpenSSH modes
 - CTR, ChaChaPoly, gEtM, AES-GCM.
5. Better security for SSH: InterMAC
6. Concluding remarks

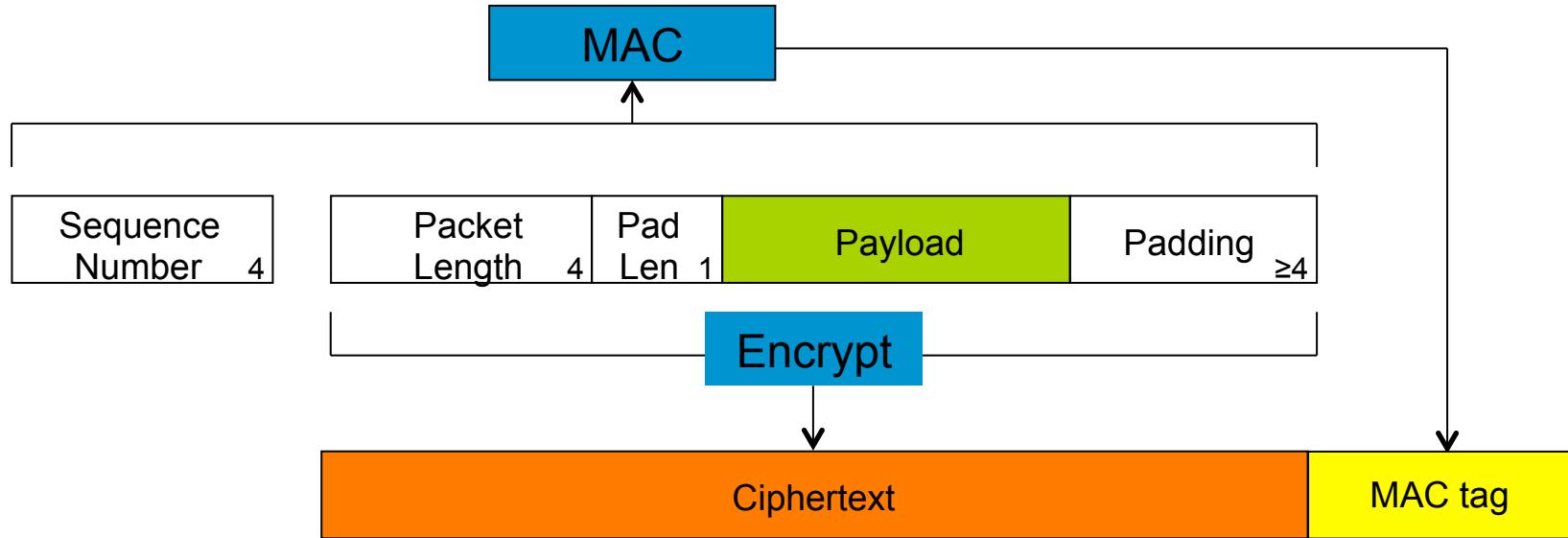
Introducing SSH and related work

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 [BKNo2]: 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 [BKNo2].
- 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 [BKNo2] 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%)
ROSSH	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%)	89,144 (0.5%)
OpenSSH_5.1	86,338 (0.5%)	44,120 (0.5%)
OpenSSH_5.3p1	84,559 (0.5%)	0 (0%)
OpenSSH_7.1	83,793 (0.5%)	0 (0%)

Mostly OpenSSH and dropbear; others less than 5%.

SSH versions

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OpenSSH_7.1	83,793 (0.5%)	0 (0.0%)	

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_6.2	255,088 (1.5%)	288,710 (1.6%)
dropbear_2013.58	236,409 (1.4%)	249,281 (1.4%)
dropbear_0.53	217,970 (1.3%)	213,611 (1.3%)
dropbear_0.52	132,668 (0.8%)	136,111 (0.8%)
OpenSSH	110,602 (0.6%)	108,511 (0.6%)
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OpenSSH_5.3p1	84,559 (0.5%)	84,111 (0.5%)
OpenSSH_7.1	83,793 (0.5%)	84,111 (0.5%)

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-@	2,010,936	(29.90%)
aes128-ctr + umac-64-@	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

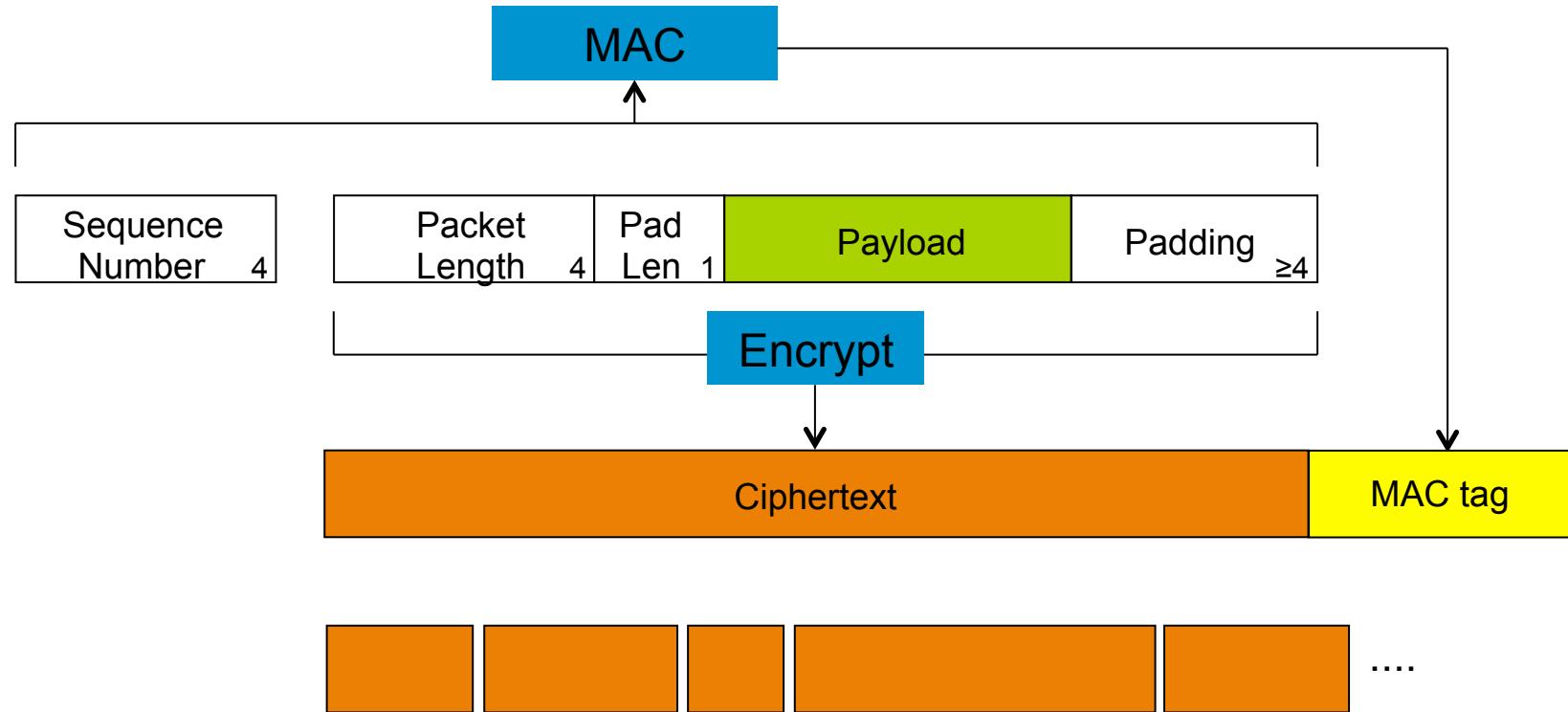
encryption and mac algorithm	count	
aes128-ctr + hmac-sha1-96	8,724,863	(90.44%)
aes128-cbc + hmac-sha1-96	478,181	(4.96%)
3des-cbc + hmac-sha1	321,492	(3.33%)
aes128-ctr + hmac-sha1	62,465	(0.65%)
aes128-ctr + hmac-sha2-256	36,150	(0.37%)
aes128-cbc + hmac-sha1	14,477	(0.15%)

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

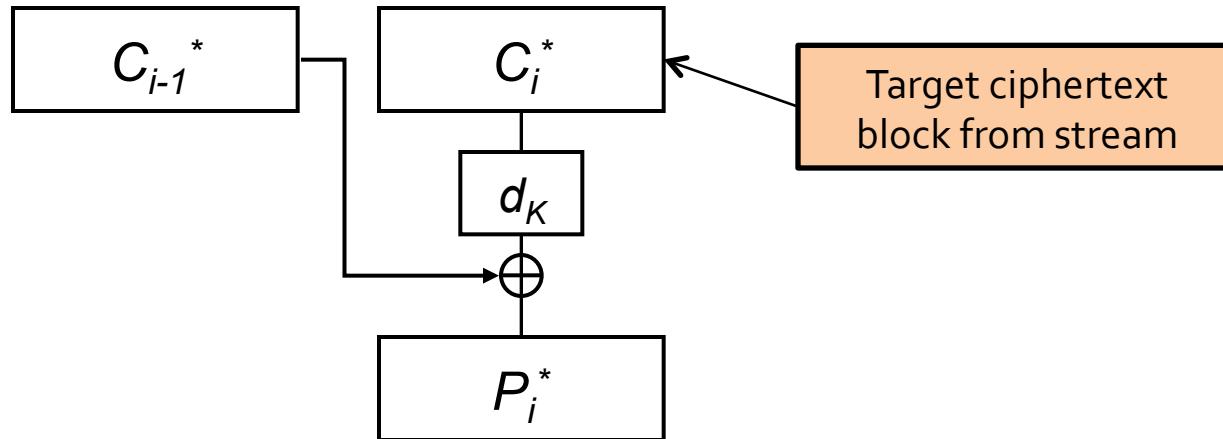


How would you perform decryption for an incoming sequence of ciphertext fragments?

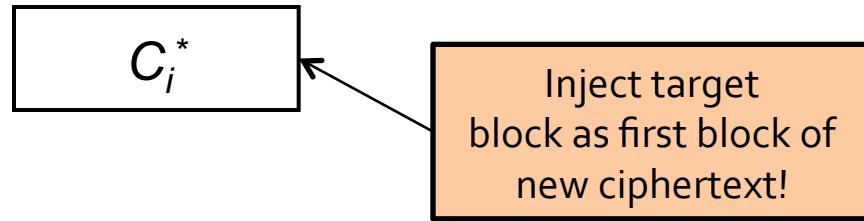
The [APWog] attack (simplified)

- 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 $\text{SQN} \parallel \text{PTXT}$ (with connection termination and error message if MAC verification fails).

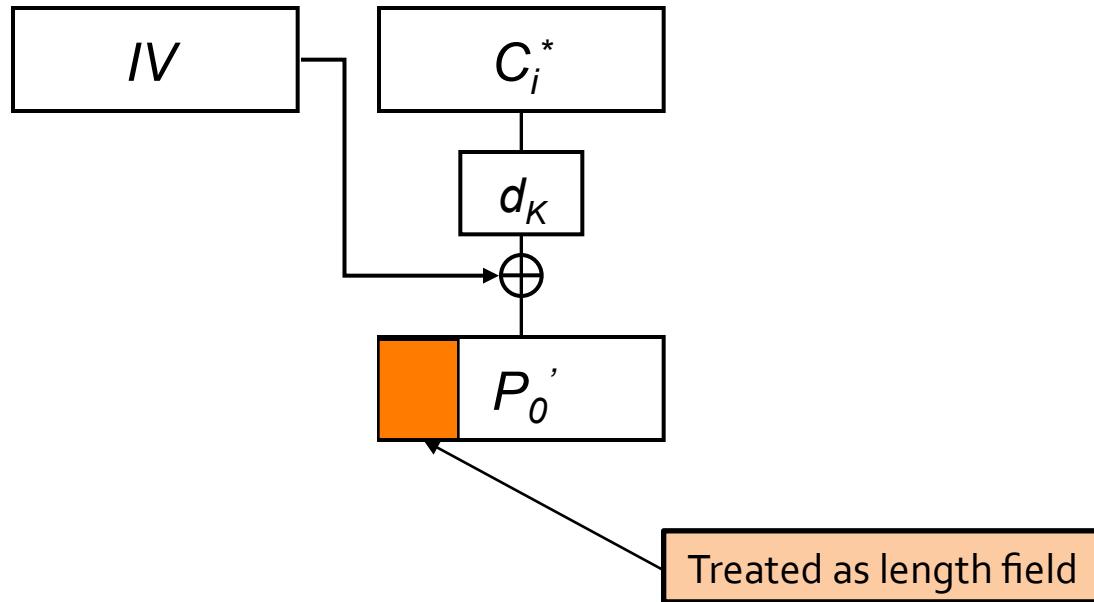
Breaking CBC mode in SSH [APW09]



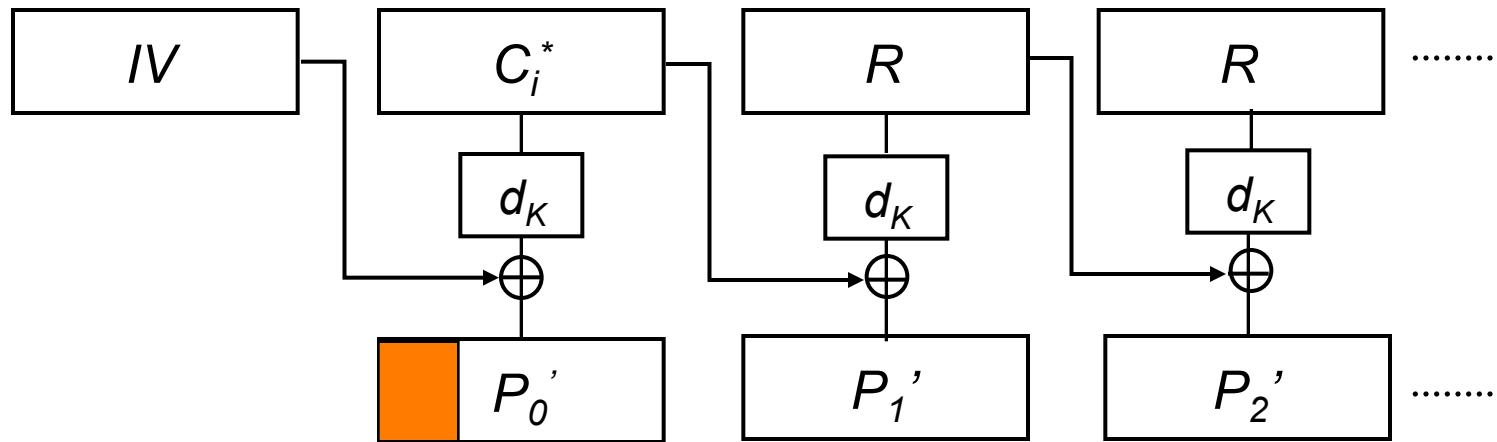
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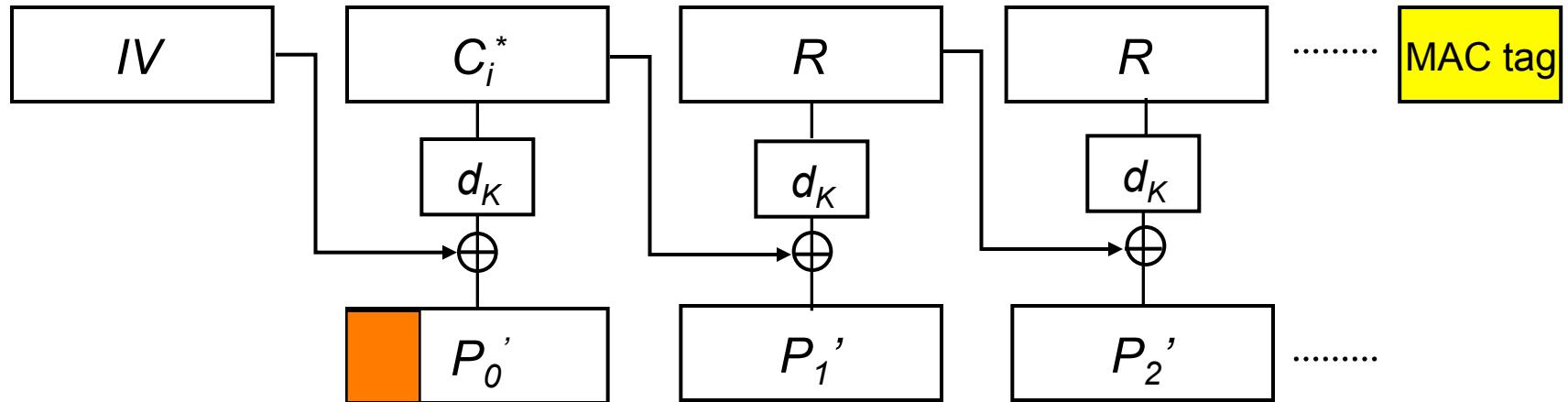
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Breaking CBC mode in SSH [APW09]

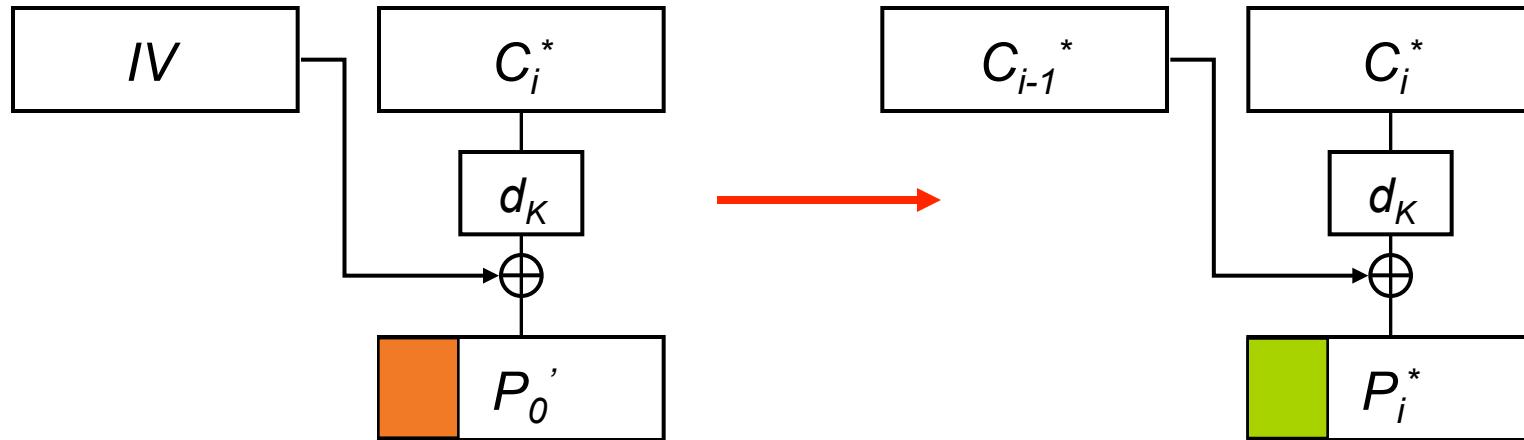


Breaking CBC mode in SSH [APW09]



- 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^* .

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

The [APWog] attack (less simplified)

- OpenSSH 5.1 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 [APWog] attack

Sanity checks:

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

→ FAIL

~~*ssh2_msg_disconnect*~~

$LF + 4 \bmod BL = 0$

↓
PASS

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

Wait for $LF + |\text{MAC}|$ 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 [APWog] attack

Sanity checks:

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

→ FAIL

~~*ssh2_msg_disconnect*~~

$LF + 4 \bmod BL = 0$

↓
PASS

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

Wait for $LF + |\text{MAC}|$ bytes

MAC on 2^{18} bytes

VERIFY

→ FAIL

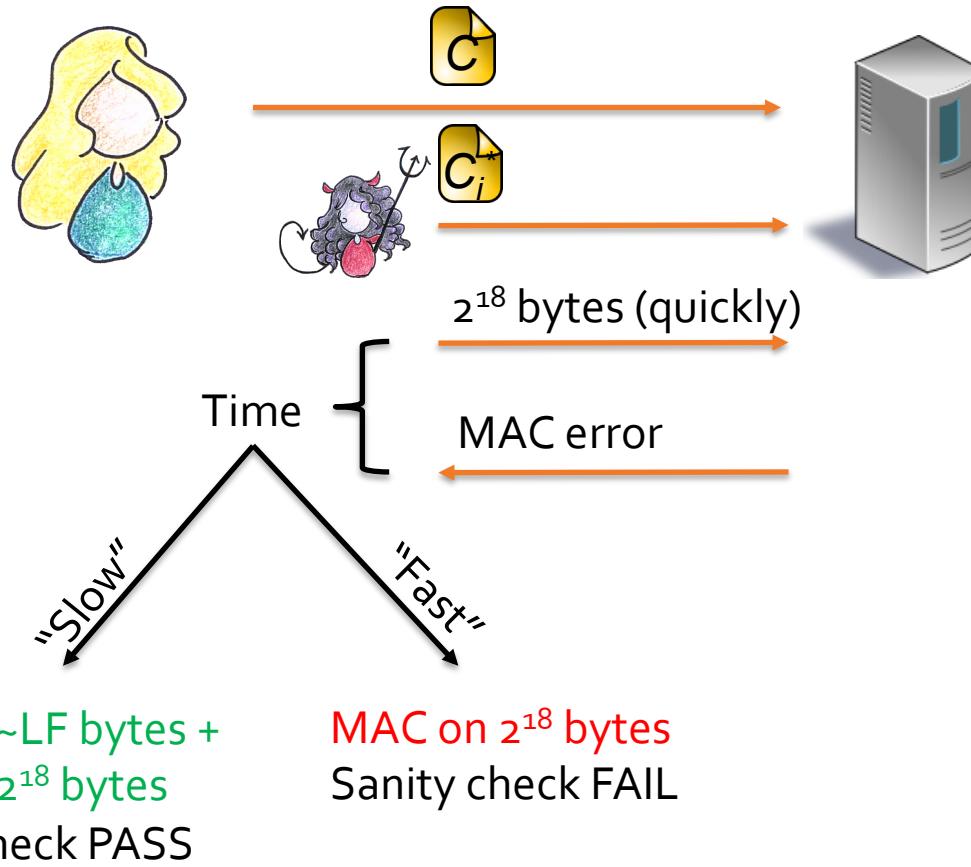
~~"corrupted MAC on input"~~

MAC on $\sim LF$ bytes +
MAC on 2^{18} bytes

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

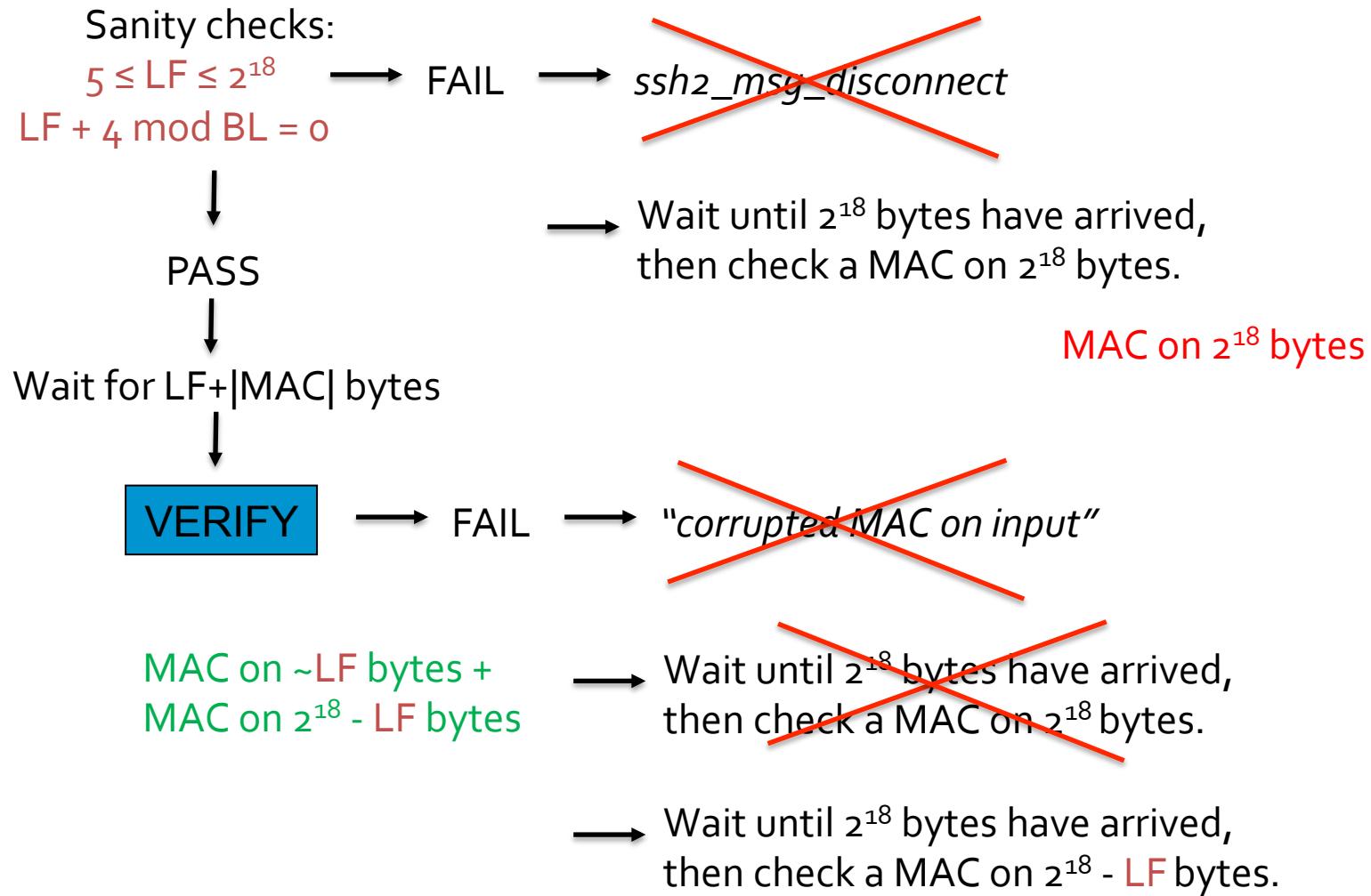
No error message is ever sent until 2^{18} bytes of ciphertext have arrived.

[ADHP16] attack against the OpenSSH 5.2 patch

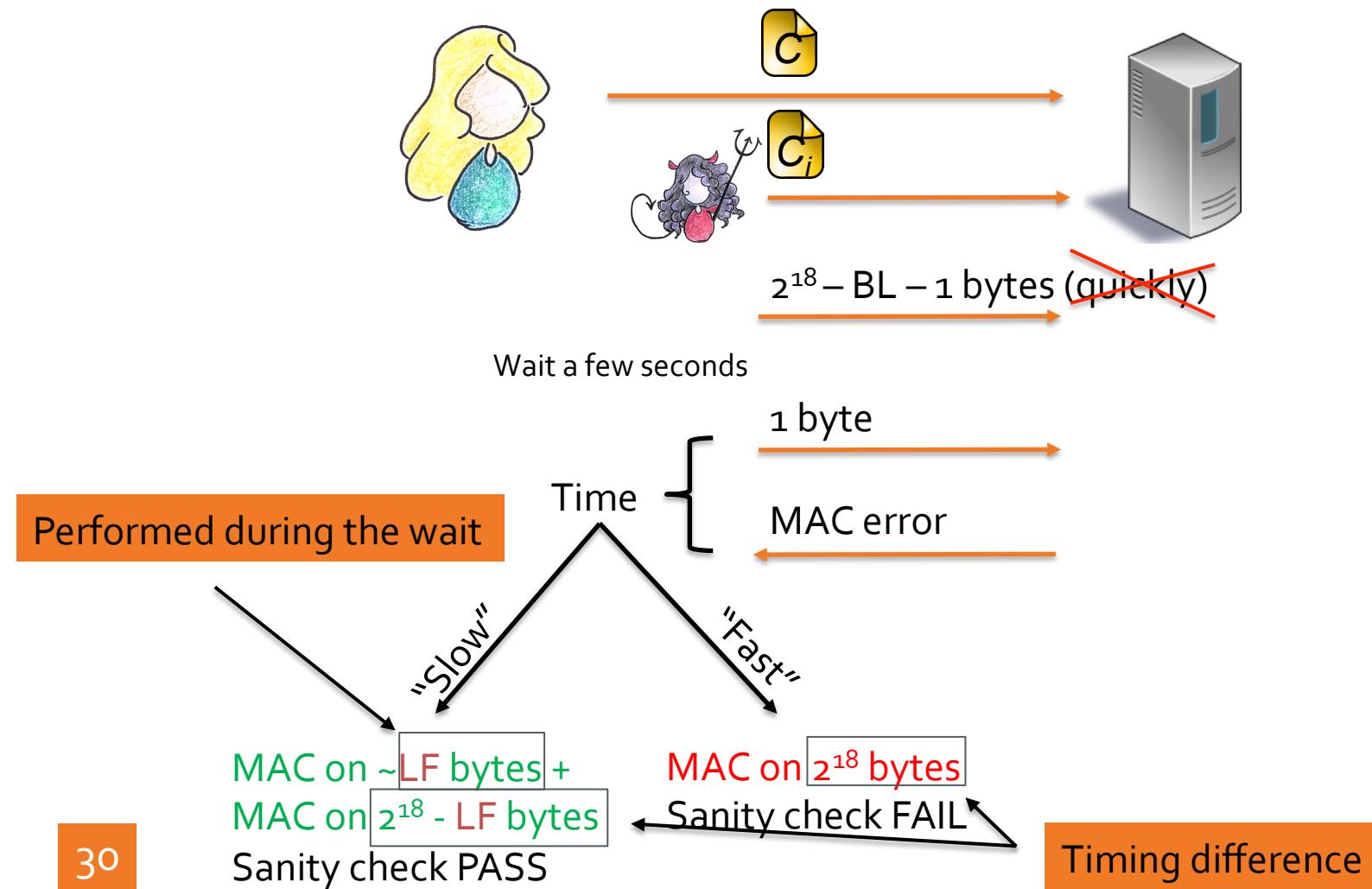


- Attacker can distinguish PASS/FAIL conditions, leaking 18 bits of plaintext.
- With careful timing, attacker can recover \sim 30 bits of plaintext.

OpenSSH 7.3 patch against [ADHP16] attack



Attacking the OpenSSH 7.3 patched patch



Attacking the OpenSSH 7.3 patched patch



Our recommended patch
actually made things
significantly worse!

Performed

“Slow”

“Fast”

MAC on \sim 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!

Disclosure of the attacks

- We first notified the OpenSSH team of the attack on the patch for the [APWog] 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.

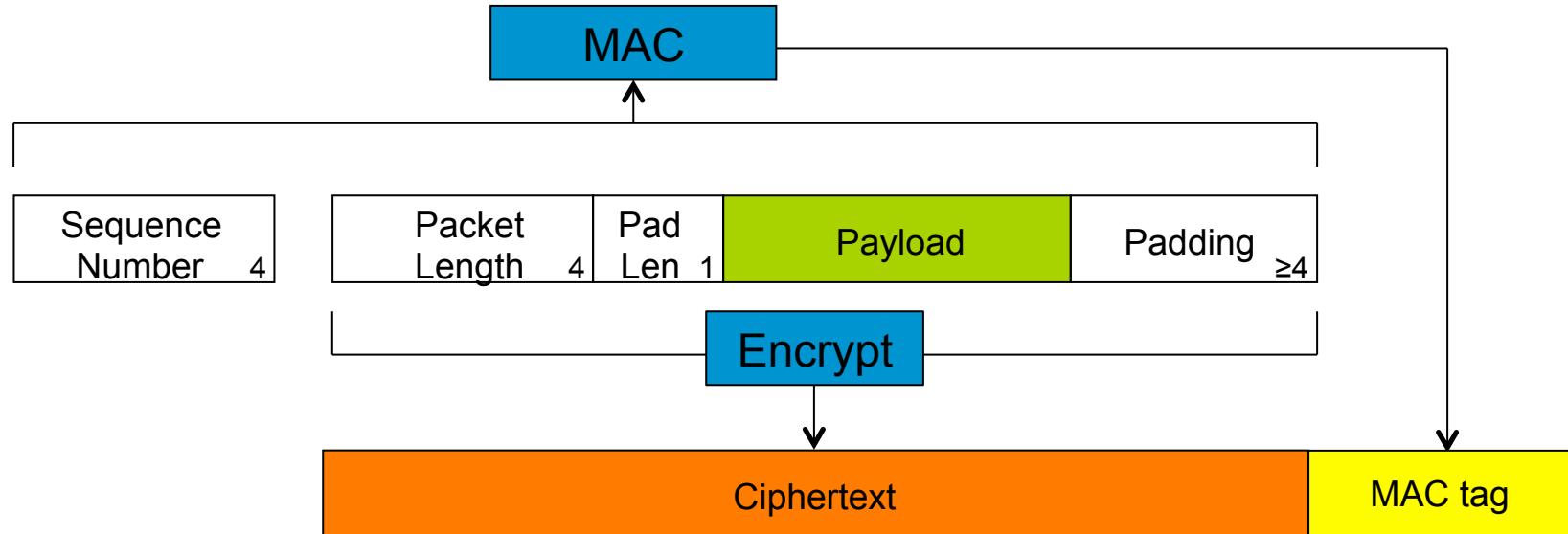
Security analysis of other SSH and OpenSSH modes – CTR, gEtM, AES-GCM, ChaCha20Poly1305

OpenSSH encryption modes

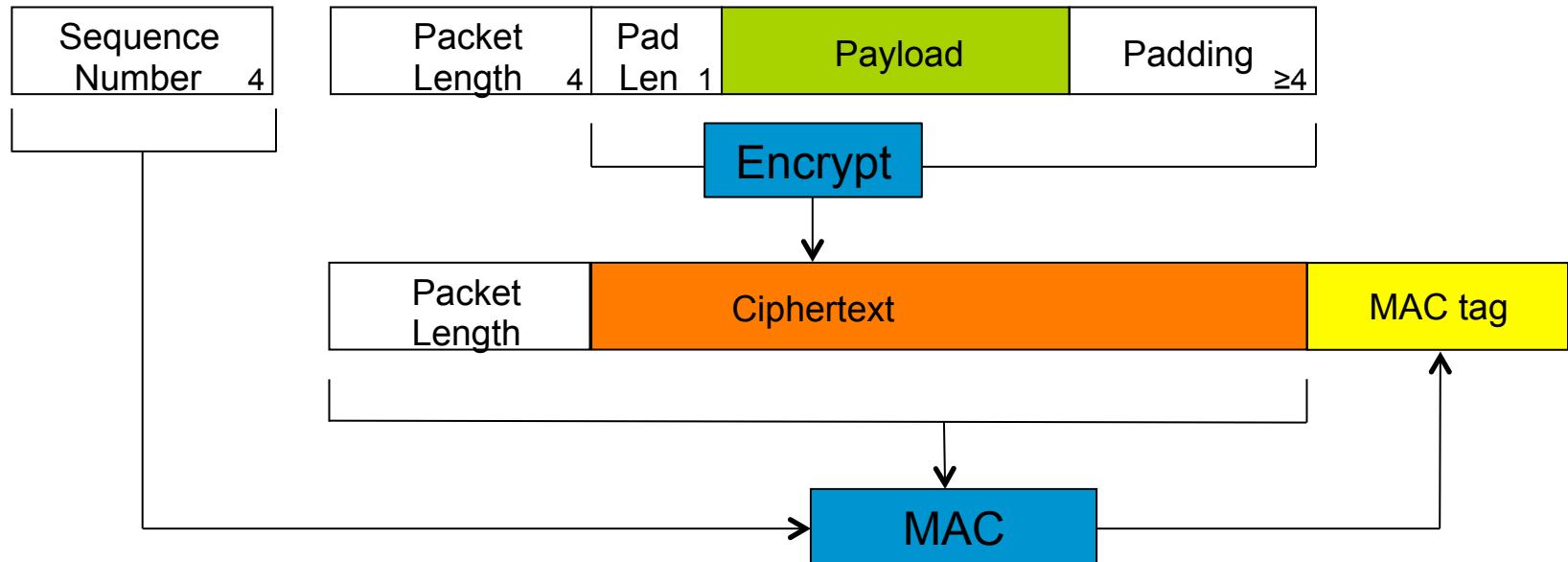
A number of new schemes have been introduced in OpenSSH since [APW09]:

- **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



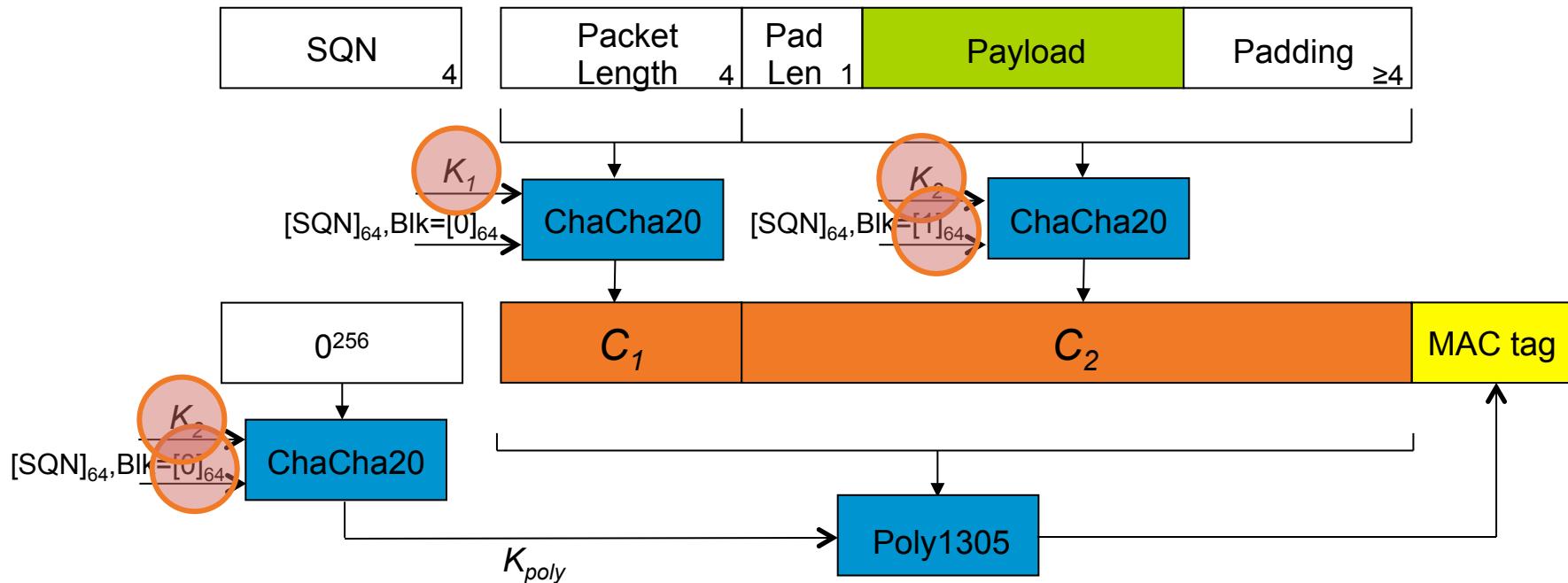
- Stateful Encode-then-EtM construction.
- AES-GCM works similarly.
- Note packet length field in the clear.
- Code = documentation.

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].

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]:

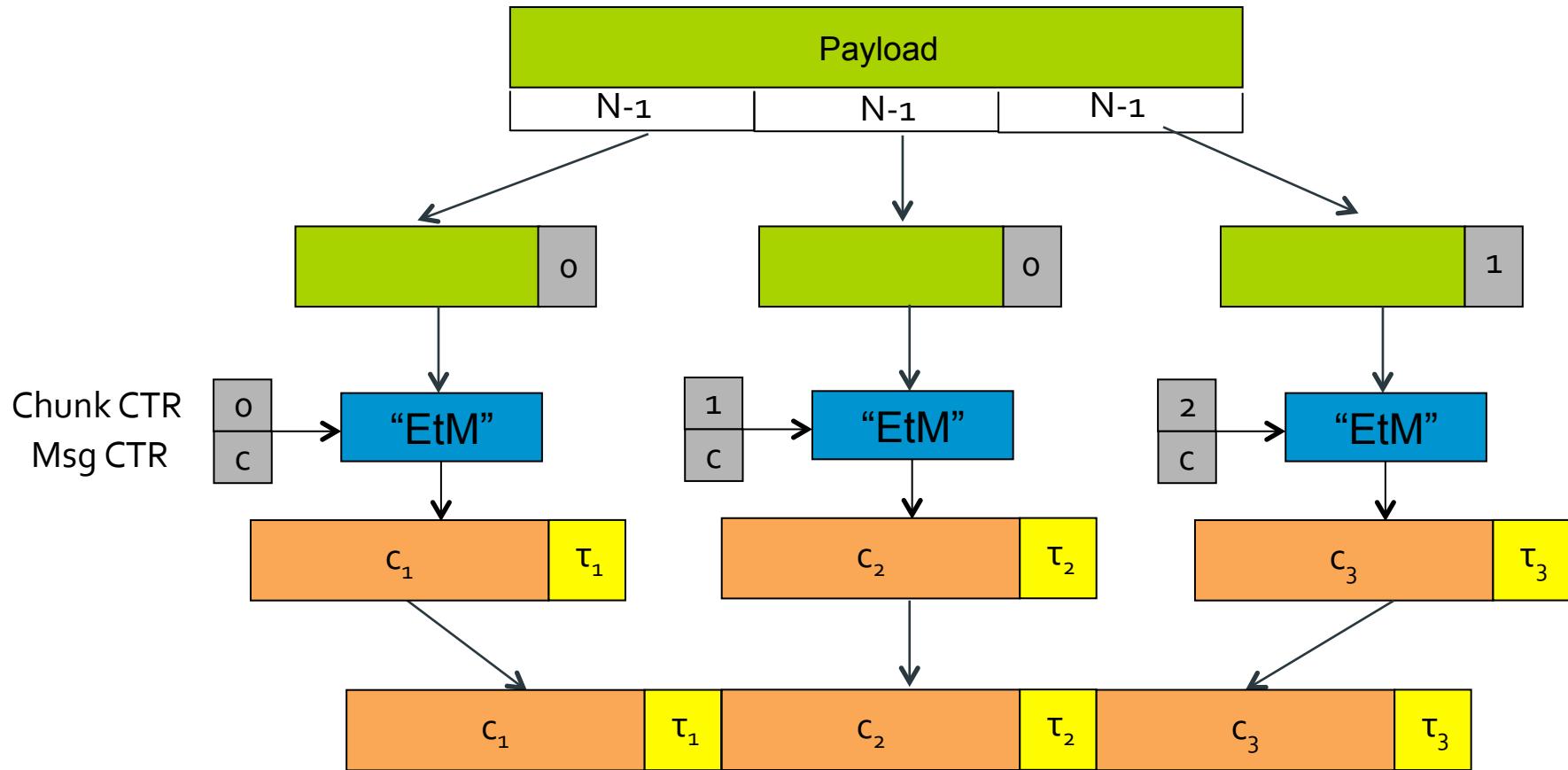
- BH-CPA (passive adversary) – boundary hiding for passive attackers.
- BH-sfCFA (active adversary) – boundary hiding for active attackers.
- n -DOS-sfCFA: decryption must produce some output (plaintext or error) after receiving at most an n -bit sequence of fragments chosen by adversary.

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, $(N + |\text{MAC}|)$ -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

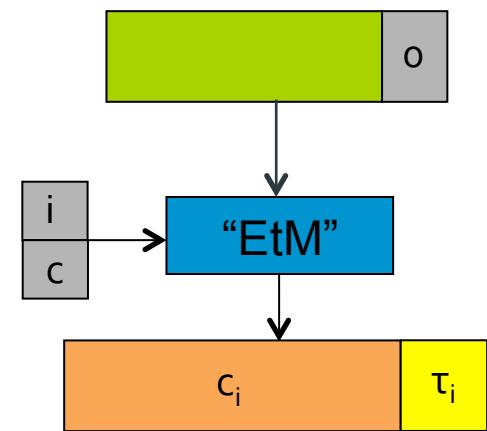


InterMAC: From Theory to Practice

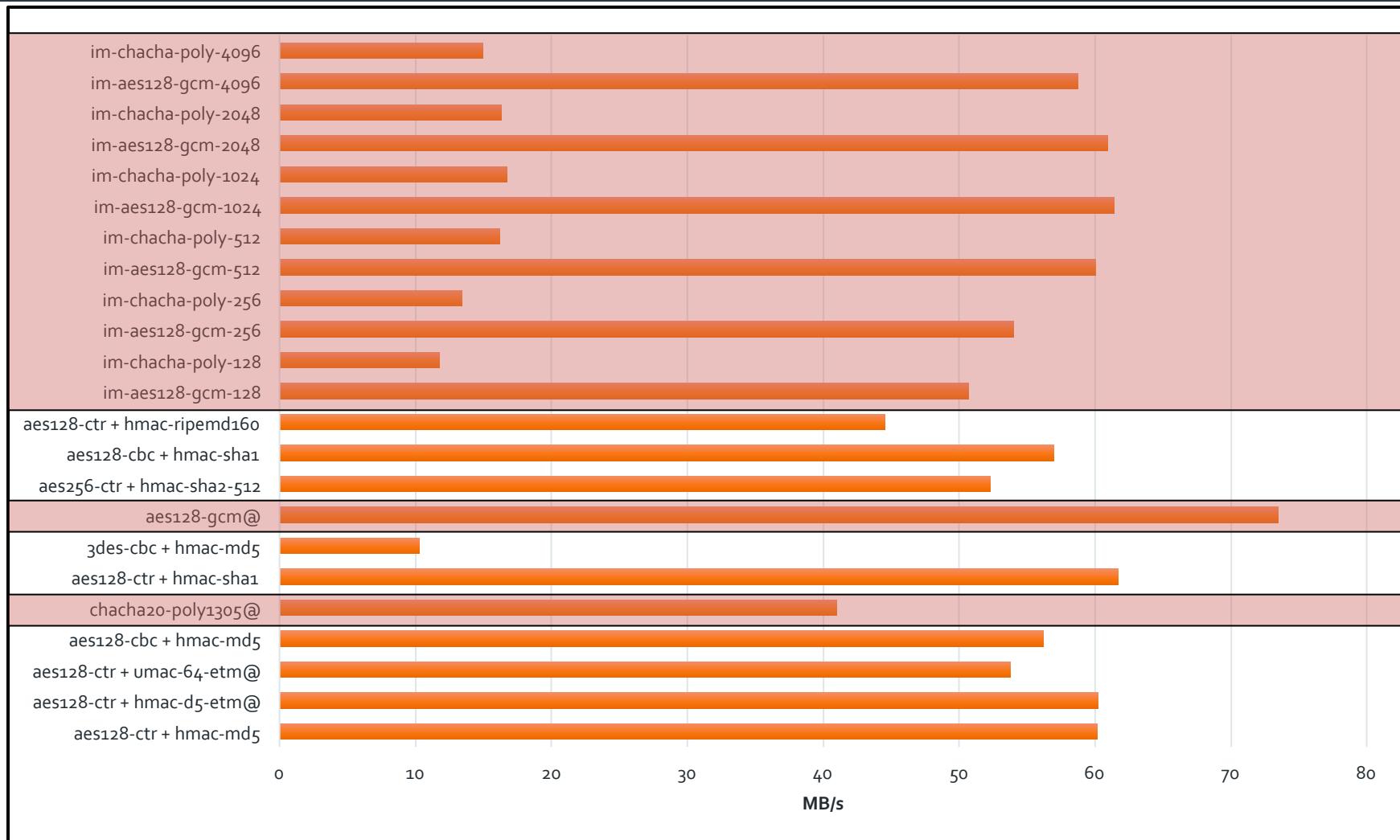
- Use byte-oriented rather than bit-oriented format.
- Abandon underlying SSH packet format (so no length field, no padding byte, no random padding).
- Need some kind of plaintext padding (length not usually a multiple of $N-1!$): variant of ABYTE padding.
- Replace EtM with nonce-based AEAD, e.g. AES-GCM 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

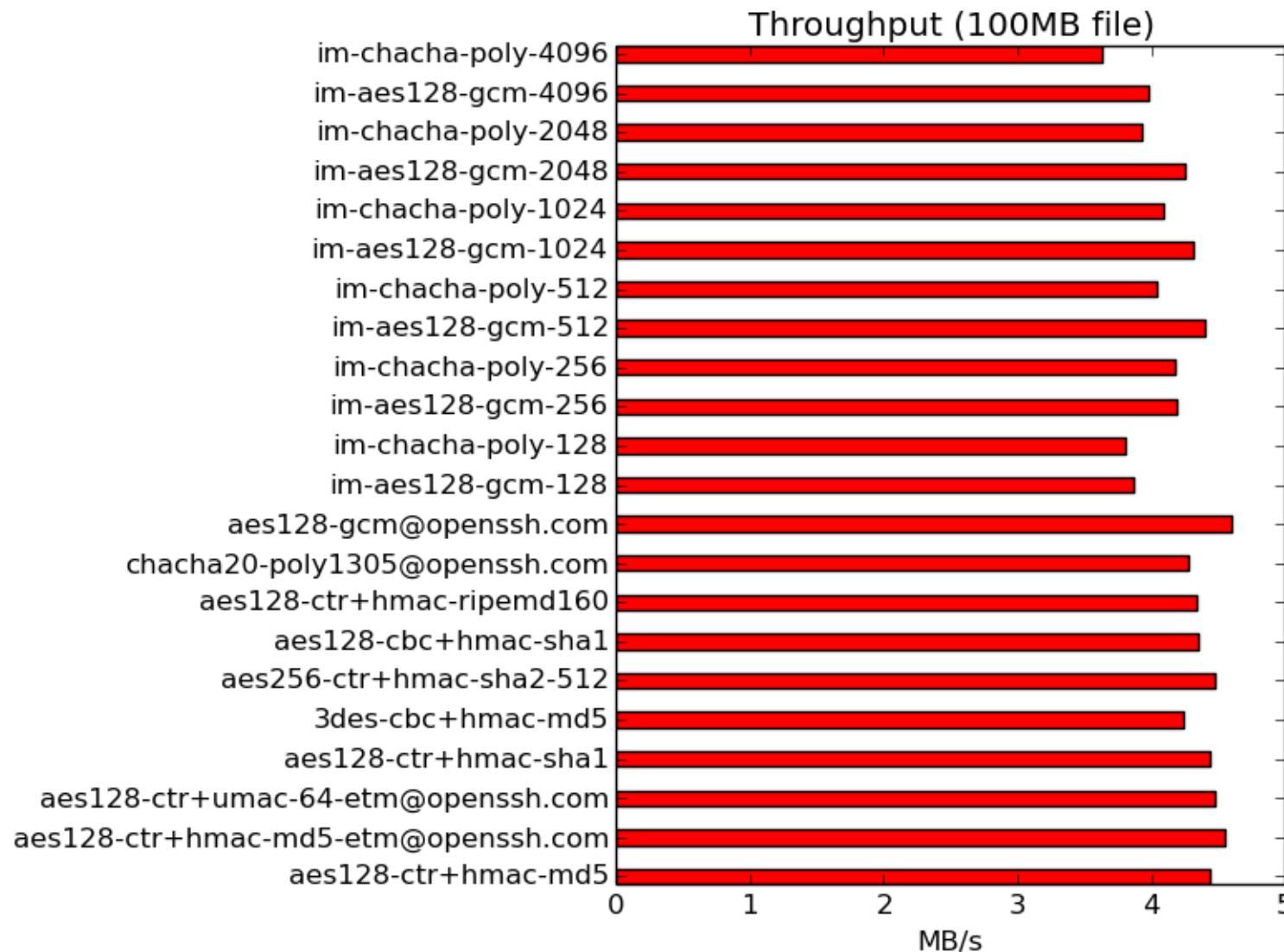
- C-implementation of InterMAC.
- Aim is to make the library easy to use for a developer.
- API: **im_initialise**, **im_encrypt**, **im_decrypt**.
- Message counter and nonce management done by the library.
- Currently supports ChaCha-Poly and AES-GCM.
- Easy to extend with other AEAD schemes.
- POC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



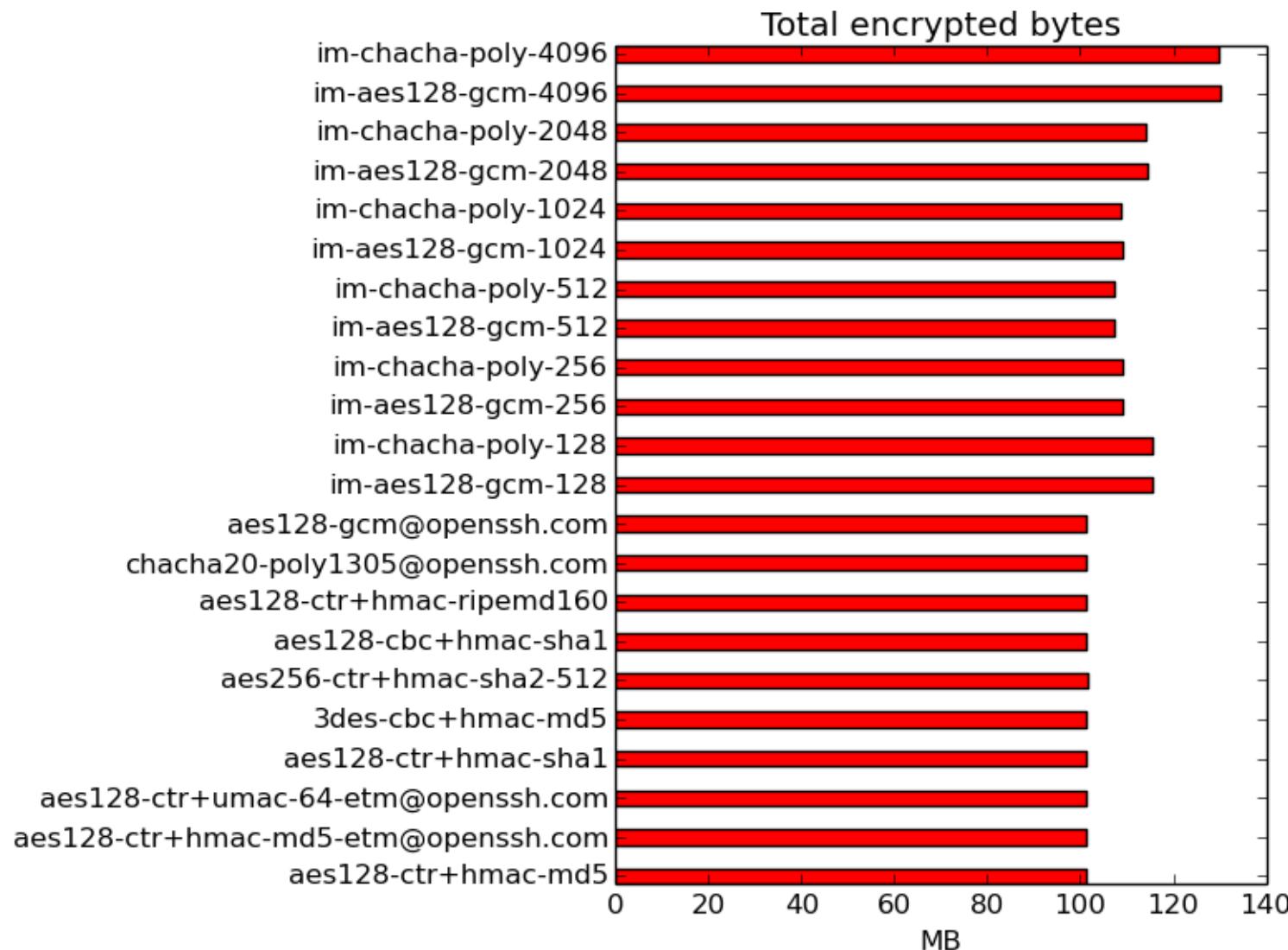
InterMAClib Throughput – SCP on Loopback



InterMAClib Throughput – AWS_London to AWS_Oregon.



InterMAClib Total Bandwidth – AWS_London to AWS_Oregon.



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
- 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 on-going work, we are developing and prototyping efficient, provably secure alternatives that have all the desired properties.

Selected Literature

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