# Security and Cryptography 2020

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## X. COMMUNICATION SECURITY

**many mistakes in practice:**

- risk of common (standard) groups
- cryptanalysis: most efficient number field sieve (NFS):
  - complexity subexponential (for $\mathbb{Z}_p$ it is $\exp(1.93 + o(1))(\log p^{1/3}(\mathrm{loglog}\, p)^{2/3})$
  - most time precomputation independent from the target number $y$ (where $\log y$ to be computed in a given group)
  - the time dependant from $y$ can be optimized to subexponential but much lower
  - 512-bit groups can be broken, MitM attack can be mounted

- standard safe primes – seem to be ok, but attacker can amortize the cost over many attacks
- TLS with DH: frequently "export-grade" DH with 512 bit primes, about 5% of servers support DHE_EXPORT, most servers (90% and more) use a few primes of a given length, after a precomputation breaking for a given prime: reported as 90 sec
- TLS: client wants DHE, server offers DHE_EXPORT, but one can manipulate the messages exchanged, so that the client treats the $(p_{512}, g, g^b)$ as a response to DHE – it is not an implementation bug!
- sometimes non safe prime used (the number $\frac{p-1}{2}$ is composite), Pohling-Hellman method can be used
- DH-768 breakable on academic level, claims: DH-1024 for state agencies in some countries
- recommendations:
  - avoid fixed prime groups
  - transition to EC (partially withdrawn due to required transition to post-quantum instead)
  - deliberately do not downgrade security, even if seems to be ok
  - follow the progress in computer algebra

**Padding attack** (Serge Vaudenay)

**Attacked scenario:**

- for encryption the plaintext should consist of some number of blocks of length $b$
- padding is always applied (even if unnecessary)
- if $i$ positions have to be padded, write $i$ times the number $i$ . de-padding is obvious
- encrypt the resulting padded plaintext $x_1,\ldots,x_N$ in the CBC mode with IV (fixed or random) and a block cipher $\mathrm{Enc}$:

$$y_1 = \mathrm{Enc}(\mathrm{IV} \oplus a_1), \quad y_i = \mathrm{Enc}(y_{i-1} \oplus x_i)$$

- properties of CBC:
  - efficiency
  - a warning about confidentiality weakness: if IV fixed, then one can check that two plaintexts have the same prefix of a given size

**attack:**

- manipulate the ciphertext
- destination node decrypts, it can detect incorrect padding
- decision: what to do if the padding is incorrect? Each reaction will turn out to be wrong:
  - $\longrightarrow$ reaction "reject": creates padding oracle (attacker tests the behavior)
  - $\longrightarrow$ reaction "proceed": enables manipulation of the plaintext data

**option "reject", last word oracle:**

- goal: compute $a = \mathrm{Dec}(y)$ for a block $y$
- create an input for the padding oracle:
  - create a 2 block ciphertext: $r = r_1 \ldots r_b$ chosen at random, $c := r|y$
  - oracle call: if $\mathrm{Oracle}(c) = \mathrm{valid}$, then $\mathrm{Dec}(y) \otimes r$ should yield a correct padding. whp this happens if $a_b = r_b \oplus 1$ (that is, if the padding consists of a single "1"). Other options: suffix "22", "333", "4444",.... are less probable

– it may happen that the oracle says `valid` because of other correct padding. The following procedure solves the problem (idea: change consequtive words in the padding until invalid:

1 pick $r_1, r_2..., r_b$ at random, take $i = 0$

2 put $r = r_1 r_2 ... r_{b-1}(r_b \oplus i)$

3 run padding oracle on $r|y$, if the result `invalid` then increment $i$ and goto (2)

4 $r_b := r_b \oplus i$ /* now we have a correct padding of an unknown length

5 for $j = b$ to 2:

$r := r_1 ... r_{b-j}(r_{b-j+1} \oplus 1) r_{b-j} ... r_b$

/* attempting to disturb padding, from left to right

ask padding oracle for $r|y$, if `invalid` then output $(r_{b-j+1} \oplus j)...(r_b \oplus j)$ and halt

6 output $r_b \oplus 1$ /* last choice, manipulating all positions except the rightmost has not created an error so the padding has length 1, so $y_b \oplus r_b = 1$ or $y_b = r_b \oplus 1$

## block decryption oracle

let $a_1 \ldots a_b$ be the plaintext of $y$

decryption:

– get $a_b$ via the last word oracle

– proceed step by step learning $a_{j-1}$ once $a_j, \ldots, a_b$ are already known

  1 set $r_k := a_k \oplus (b - j + 2)$ for $k = j, \ldots, b$ /* preparing the values so that the padding values $(b - j + 2)$ appear at the end)

  2 set $r_1, \ldots, r_{j-1}$ at random, $i := 0$ /* search for the value that makes a proper padding

  3 $r := r_1 \ldots r_{j-2}(r_{j-1} \oplus i) r_j \ldots r_b$

  4 if output on $r|y$ is `invalid`, then $i := i + 1$ and goto 3

  5 output $r_{j-1} \oplus i \oplus (b - j + 2)$

## decryption oracle

– block by block, (after decryption we have to XOR with the previous ciphertext block due to CBC construction)

– the only problem is the first block if IV is secret

**bomb oracles:**

- padding oracle in SSL/TLS breaks the connection if a padding error occurs , so it can be used only once
- bomb oracle: try a longer part at once, execute many trials

**other paddings:**

easy to adjust the attack in the following cases (the reason is that we KNOW hat to expect on a given position of the padding) :

- $00....0n$ instead of $nn....n$
- $12....n$ instead of $nn....n$

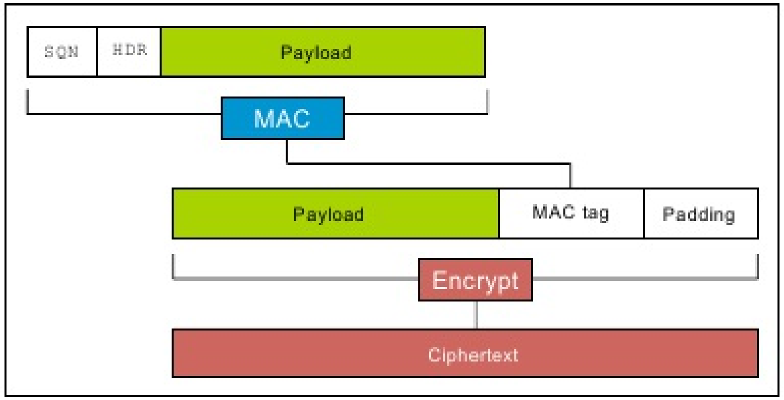
the padding where it would not work is a padding with random data on the added positions

**Applications for (old) versions of SSL/TLS**, ...

- if MAC applied before padding, then padding oracle techniques can be applied
- wrong MAC and wrong padding create the same error message - from SSL v3.0, debatable whether it is impossible to recognize the situation via side channel (response time)
- TLS attempts to hide the plaintext length by variable padding:
  - checking the length of padding: take the last block $y$, send $r|y$ where the last word of $r$ is $n \oplus 1$. acceptance indicates that the padding is of length
- IPSEC: discards message with a wrong padding, no error message, but there might be other activities to process errors (they may leak information)
- WTLS: *decryption-failed* message in clear (!) session not interrupted
- SSH: MAC after padding (+)

## Lucky Thirteen

- concerns DTLS (similar to TLS for UDP connections)
- MAC-Encode-Encrypt paradigm (MEE), MAC is HMAC based




- 8-byte SQN, 5-byte HDR (2 byte version field, 1 byte type field, 2 byte length field)
- size of the MAC: 16 bytes (HMAC-MD5), 20 bytes (HMAC-SHA1), 32 bytes (HMAC-SHA-256)
- padding: $p+1$ copies of $p$, at least one byte must be added
- after receiving: checking the details: padding, MAC, (underflow possible if padding manipulated and padding removed blindly)
- HMAC of $M$:

  $T := H((K_a \oplus \text{opad}) || H((K_a \oplus \text{ipad}) || M))$

- **Distinguishing attack:**
  - $\rightarrow$ $M_0$ : 32 arbitrary bytes followed by 256 copies of 0xFF (11111111 in binary)
  - $\rightarrow$ $M_1$: 287 bytes followed by $0x00$
  - $\rightarrow$ both $M_0$ and $M_1$ consist of 288 bytes, plaintext consists of 18 16-byte blocks
  - $\rightarrow$ encoded $M_d||T||\text{pad}$, we aim to guess $d$
  - $\rightarrow$ $C =$ the resulting ciphertext
  - $\rightarrow$ create a ciphertext $C'$ by truncating all parts of $C$ corresponding to $T||\text{pad}$
  - $\rightarrow$ give HDR$||C'$ for decryption
  - $\rightarrow$ for $M_0$: the 256 copies of 0xFF interpreted as padding and removed, remaining 32 bytes treated as a short message and MAC, calculating MAC: 4 hash block operations, then typically error returned to the attacker
  - $\rightarrow$ if $M_1$: 8 hash evaluations as HMAC computed over a long message (then typically an error)

## Plaintext recovery attacks for CBC encrypted transmission

- $C^*$ – the block of ciphertext to be broken, $C'$ – the ciphertext block preceding it
- we look for $P^*$, where $P^* = \mathrm{Dec}(C^*) \oplus C'$
- assume CBC with known IV, $b = 16$ (as for AES). $t = 20$ (as for HMAC-SHA-1)
- let $\Delta$ be a block of 16 bytes, consider

$$C^{\mathrm{att}}(\Delta) = \mathrm{HDR}||C_0||C_1||C_2||C' \oplus \Delta||C^*$$

it represents 4 non-IV blocks in the plaintext, the last block is:

$$P_4 = \mathrm{Dec}(C^*) \oplus (C' \oplus \Delta) = P^* \oplus \Delta$$

- case 1: $P_4$ ends with 0x00 byte:
  - 1 byte of padding is removed, the next 20 bytes interpreted as MAC, 43 bytes left -say $R$. MAC computed on SQN|HDR|$R$ of 56 bytes
- case 2: $P_4$ ends with padding pattern of $\geq 2$ bytes:
  - at least 2 bytes of padding removed, 20 bytes interpreted as MAC, at most 42 bytes left, MAC over at most 42+13=55 bytes
- case 3: $P_4$ ends with no valid padding:
  - according to RFC of TLS 1.1, 1.2 treated as with no padding , 20 bytes treated as MAC, verification of MAC over 44+13=57 bytes

    – MAC is computed to avoid other timing attacks!

- time: case 1 and 3: 5 evaluations of SHA-1, case 2: 4 evaluations of SHA-1, detection of case 2 possible in LAN
- in case 2: most probable is the padding 0x01 0x01, all other paddings have probability about $\approx \frac{1}{256}$ of probability of 0x01 0x01, so we may assume that $P_4 = P^* \oplus \Delta$ ends with 0x01 0x01. Then we derive the last two bytes of $P^*$.

  repeat the attack with $\Delta'$ that has the same last two bytes as $\Delta$ to check if the padding has the length bigger than 2 (we are changing the byte 3 and observe whether the case 2 occurs, if it is so, then padding has length 2).
- after recovery of the last two bytes the rest recovered byte by byte from right to left:
  - the original padding attack
  - e.g. to find 3rd rightmost byte set the last two bytes $\Delta$ so that $P_4$ ends with 0x02 0x02, then try different values for the $\Delta$ so that Case 2 occurs (meaning that $P_4$ ends with 3 bytes 0x02
  - average time: $14 \cdot 2^7$ trials

- practical issues:
  - $\longrightarrow$ for TLS after each trial connection broken, so multi-session scenario
  - $\longrightarrow$ timing difference small, so necessary to gather statistical data
  - $\longrightarrow$ complexity in fact lower, since the plaintexts not from full domain: e.g. http username and password are encoded Base64
  - $\longrightarrow$ partial knowledge may speed up the recovery of the last 2 bytes
  - $\longrightarrow$ less efficient configuration of the lengths for HMAC-MD5 and HMAC-SHA-256

## BEAST

attack, phase 0:

1. $P$ to be recovered (e.g. a password, cookie, etc), requires ability to force Alice to put secret bits on certain positions
2. force Alice to send $0...0P_0$ (requires malware on Alice computer) – of course encrypted
3. eavesdrop and get $C_p = \mathrm{Enc}(C_{p-1} \oplus 0...0P_0)$
4. guess a byte $g$
5. force Alice to send encrypted plaintext $C_{i-1} \oplus C_{p-1} \oplus 0...0g$ :

   then Alice sends $C_i = \mathrm{Enc}(C_{i-1} \oplus C_{i-1} \oplus C_{p-1} \oplus 0...0g) = \mathrm{Enc}(C_{p-1} \oplus 0...0g)$
6. if $C_i = C_p$ then $P_0 = g$

attack phase 1:

1. $P_0$ already known
2. force Alice to send $0...0P_0P_1$ and proceed as in phase 0

last phase: we get the test for the whole $P_0...P_{15}$

protection: browser must be carefully designed and do not admit injecting plaintexts (SOP- Same Origin Protection). Some products do not implement it.

## CRIME (2012)

- based on compression algorithm used by some (more advanced) versions of TLS
- compression: LZ77 and then Huffman encoding, LZ77- sliding window approach: instead of a string put a reference to a previous occurence of the same substring
- idea of recovering cookie:

```
POST / HTTP/1.1
Host: example.com
User-Agent: Mozilla/5.0 (Windows NT 6.1; WOW64; rv:14.0) Gecko/20100101 Firefox/14.0.1
Cookie: secretcookie=7xc89f94wa96fd7cb4cb0031ba249ca2
Accept-Language: en-US,en;q=0.8

(... body of the request ...)
```

Listing 1: *HTTP request of the client*

modified POST:

```
POST /secretcookie=0 HTTP/1.1
Host: example.com
User-Agent: Mozilla/5.0 (Windows NT 6.1; WOW64; rv:14.0) Gecko/20100101 Firefox/14.0.1
Cookie: secretcookie=7xc89f94wa96fd7cb4cb0031ba249ca2
Accept-Language: en-US,en;q=0.8

( ... body of the request ...)
```

Listing 2: *HTTP request modified by the attacker*

– LZ77 compresses the 2nd occurence of secretcookie= or secretcookie=0. We try all

secretcookie=i to find out the case when compression is easier (secretcookie=7)

when the first character recovered the attacker repeats the attack for the second character (trying all "secretcookie=7i" in the preamble)

## TIME

- again based on compression but now on the server's side (from the client to the server compression might be disabled and CRIME fails)
- works if the server includes the client's request in the response (most do!)
- works even if SOP is enabled. SOP does not control data with the tag `img`, so the attacker can manipulate the length and therefore influence the number of blocks for block encryption
- the attacker requires malicious Javascript on the client's browser
- the attacker tries to get the secret value sent from the server to the client
- mechanism:
  - $\longrightarrow$ as in CRIME, the request sends "secretvalue=x" where x varies
  - $\longrightarrow$ the response is compressed, so it takes either "secretvalue=" or "secretvalue=x"
  - $\longrightarrow$ the length manipulated so that either one or two packets are sent – connection specific data must be used: Maximum Transmission Unit
  - $\longrightarrow$ RTT (round trip time) measured
- independent on the browser, it is not an implementation attack!
- countermeasure: restrict displaying images

## BREACH

Browser Reconnaissance and Exfiltration via Adaptive Compression of Hypertext

- attack against HTTP compression and not TLS compression as in case of CRIME
- a victim visits attacker-controlled website (phishing etc).
- force victim's computer to send multiple requests to the target website.
- check sizes of responses

```
GET /product/?id=12345&user=CSRFtoken=<guess> HTTP/1.1
Host: example.com
```

Listing 4: *Compromised HTTP request*

```
<form target="https://example.com:443/products/catalogue.aspx?id=12345&user=CSRFtoken=<guess>" >
...
<td nowrap id="tdErrLgf">
<a href="logoff.aspx?CSRFtoken=4bd634cda846fd7cb4cb0031ba249ca2">Log Off</a></td>
```

Listing 5: *HTTP response*

- requirements: application supports http compression, user's input in the response, sensitive data in the response
- countermeasures:
  - $\longrightarrow$ disabling compression
  - $\longrightarrow$ hiding length (randomizing the length of the output – it makes the attacks only harder if the attack can be repeated many times)
  - $\longrightarrow$ no secrets in the same response as the user's data
  - $\longrightarrow$ masking secret: instead of $S$ send $R||S \oplus R$ for random $R$ (fresh in each response)
  - $\longrightarrow$ trace behaviour of requests and warn the user

**POODLE** (2014)

in SSL v.3.0 using technique from BEAST:

- padding is not covered by MAC so the attacker can manipulate it
- padding non-deterministic: padding 1 to $L$ bytes ($L$= block length, say 16), the last byte denotes the number of preceding padding random bytes
- encrypted POST request:

  POST /path Cookie: name=value... ⟨r\n\r\n⟩ body ||20-byte MAC||padding
- manipulations such that:
  - the padding fills the entire block (encrypted to $C_n$)
  - the last unknown byte of the cookie appears as the last byte in an earlier block encrypted into $C_i$
- attack: replace $C_n$ by $C_i$ and forward to the server

  usually reject

  accept if $\mathrm{Dec}_K(C_i)[15] \oplus C_{n-1}[15] = 15$, thereby $P_i[15] = 15 \oplus C_{n-1}[15] \oplus C_{i-1}[15]$

  proceed in this way byte by byte
- downgrade dance: provoke lower level of protection by creating errors say in TLS 1.0, and create connection with SSL v3.0
- the attack does not work with weak (!) RC4 because of no padding

## Weaknesses of RC4

- known weaknesses:
  - → the first 257 bytes of encryption strongly biased, $\approx 200$ bytes can be recovered if ≈232 encryptions of the same plaintext available

    simply gather statistics as in case of Ceasar cipher
  - → at some positions (multiplies of 256) if a zero occurs, then the next position more likely to contain a zero
- broadcast attack: force the user to encrypt the same secret repeatedly and close to the beginning
- countermeasure: no secrets in the initial part!

## TLS 1.2

differences with TLS 1.1 and TLS 1.0:

- explicit IV instead of implicit IV
- IDEA and DES 64bit removed
- MD5/SHA-1 is replaced with a suite specified hash function – SHA-256 for all TLS 1.2 suites, but in the future also SHA-3, ....
- digitally-signed element includes the hash algorithm used
- Verify_data length is no longer fixed length $\Rightarrow$ TLS 1.2 can define SHA-256 based cipher suites
- new encryption modes allowed: CCM, GCM

**CCM** encryption mode (Counter with CBC-MAC)

just to avoid patent threats (triggered by request to patent OCB mode - patented in USA, exempt for general public license for non-commertial use)

**Prerequisites:** block cipher algorithm; key $K$; counter generation function; formatting function; MAC length $Tlen$

**Input:** nonce $N$; payload $P$ of $Plen$ bits; valid associated data $A$

**Computation:** Steps:

1. formatting applied to $(N, A, P)$, result: blocks $B_0, \ldots, B_r$
2. $Y_0 := \mathrm{Enc}_K(B_0)$
3. for $i = 1$ to $r$: $Y_i := \mathrm{Enc}_K(B_i \oplus Y_{i-1})$
4. $T := \mathrm{MSB}_{Tlen}(Y_r)$
5. generate the counter blocks $\mathrm{Ctr}_0, \mathrm{Ctr}_1, \ldots, \mathrm{Ctr}_m$ for $m = Plen/128$
6. for $j = 0$ to $m$: $S_j := \mathrm{Enc}_K(\mathrm{Ctr}_j)$
7. $S := S_1 || \ldots || S_m$
8. $C := (P \oplus \mathrm{MSB}_{Plen}(S)) || (T \oplus S_0)$

**Decryption**:

1. return INVALID, if $Clen < Tlen$
2. generate the counter blocks $\mathrm{Ctr}_0, \mathrm{Ctr}_1, ..., \mathrm{Ctr}_m$ for $m = Plen/128$
3. for $j = 0$ to $m$: $S_j := \mathrm{Enc}_K(\mathrm{Ctr}_j)$
4. $S := S_1 || ... || S_m$
5. $P := \mathrm{MSB}_{Clen}(C) \oplus \mathrm{MSB}_{Plen}(S)$
6. $T := \mathrm{LSB}_{Tlen}(C) \oplus \mathrm{MSB}_{Tlen}(S_0)$
7. If $N$, $A$ or $P$ invalid, then return INVALID, else reconstruct $B_0, ..., B_r$
8. recompute $Y_0, ..., Y_r$
9. if $T \neq \mathrm{MSB}_{Tlen}(Y_r)$, then return INVALID, else return $P$.

properties:

- data length must be known in advance
- two passes

## GCM (The Galois/Counter Mode)

background:

- popular, as replacement for CBC mode (because of attacks presented) and weaknesses of RC4 (forbidden in the current TLS)
- received fundamental critics already before standardization
- finally (April 2018) Google decided to remove it until April 2019
- operations over GF($2^{128}$), addition in the field represented by xor ($\oplus$)

**Computation:** Steps:

1. $H\!:=\!\mathrm{Enc}_K(0^{128})$

2. $Y_0\!:=\!\mathrm{IV}||0^{31}1$ if length of IV should be 96

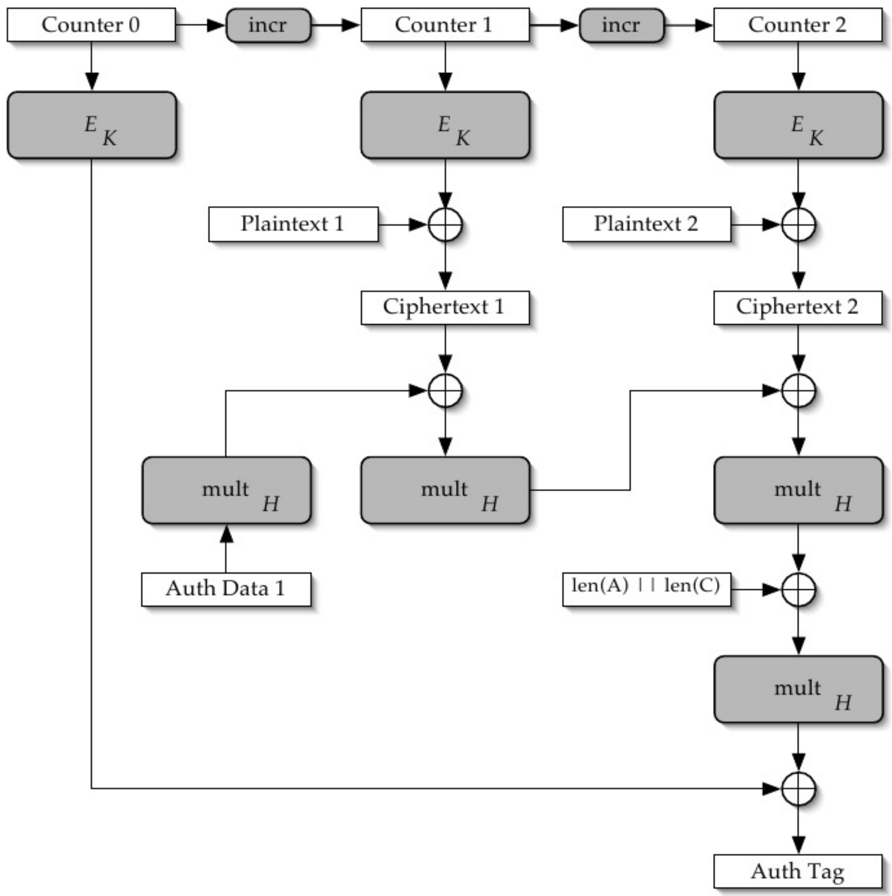
   or $Y_0\!:=\!\mathrm{GHASH}(H,\{\},\mathrm{IV})$

3. $Y_i\!:=\!\mathrm{incr}(Y_{i-1})$ for $i=1,\ldots,n$ (counter computation)

4. $C_i := P_i \oplus \mathrm{Enc}_K(Y_i)$ for $i=1,\ldots,n-1$ (counter based encryption)

5. $C_n^* := P_n \oplus \mathrm{MSB}_u(\mathrm{Enc}_K(Y_n))$ (the last block need not to be full)

6. $T := \mathrm{MSB}_t(\mathrm{GHASH}(H,A,C)) \oplus \mathrm{Enc}_K(Y_0)$




## Details of computation of the tag

$\mathrm{GHASH}(H, A, C) = X_{m+n+1}$ where $m$ is the length of authenticating information $A$, and:

$X_i$ equals:

$0$ for $i = 0$

$$(X_{i-1} \oplus A_i) \cdot H \qquad \text{for } i = 1, ..., m-1$$

$$((X_{i-1} \oplus (A_m^* || 0^{128-v})) \cdot H \qquad \text{for } i = m$$

$$(X_{i-1} \oplus C_i) \cdot H \qquad \text{for } i = m+1, ..., m+n-1$$

$$((X_{m+n-1} \oplus (C_m^* || 0^{128-u})) \cdot H \qquad \text{for } i = m+n$$

$$((X_{m+n} \oplus (\mathrm{len}(A) | \mathrm{len}(C))) \cdot H \qquad \text{for } i = m+n+1$$

**Decryption:**

1. $H := \mathrm{Enc}_K(0^{128})$
2. $Y_0 := \mathrm{IV} || 0^{31} 1$ if length of IV should be 96

   or $Y_0 := \mathrm{GHASH}(H, \{\}, \mathrm{IV})$
3. $T' := \mathrm{MSB}_t(\mathrm{GHASH}(H, A, C)) \oplus \mathrm{Enc}_K(Y_0)$ , is $T = T'$?
4. $Y_i := \mathrm{incr}(Y_{i-1})$ for $i = 1, ..., n$
5. $P_i := C_i \oplus \mathrm{Enc}_K(Y_i)$ for $i = 1, ..., n$
6. $P_n^* := C_n^* \oplus \mathrm{MSB}_u(\mathrm{Enc}_K(Y_n))$