

IEEE Standard for Wide-Block Encryption for Shared Storage Media

IEEE Computer Society

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Information Assurance Standards Committee
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Information Assurance Standards Committee
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Abstract: EME2-AES and XCB-AES wide-block encryption with associated data (EAD) modes of the NIST AES block cipher, providing usage guidelines and test vectors, are described. A wide-block encryption algorithm behaves as a single block cipher with a large plaintext input and ciphertext output, but uses a narrow block cipher [in this case Advanced Encryption Standard (AES)] internally. These encryption modes are oriented toward random access storage devices that do not provide authentication, but need to reduce the granularity of a potential attack.

Keywords: data-at-rest security, encryption, encryption with associated data (EAD), encrypt-mix-encrypt-v2 mode of operation (EME2), extended codebook mode of operation (XCB), IEEE 1619.2, security, storage

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Introduction

This introduction is not part of IEEE Std 1619.2-2010, IEEE Standard for Wide-Block Encryption for Shared Storage Media.

The purpose of this standard, similar to IEEE Std 1619-2007 [B2], is to describe a method of encryption for data stored in logical block-based devices, where the threat model includes possible access to stored data by the adversary.^a As in IEEE Std 1619-2007, this standard specifies length-preserving encryption algorithms to be applied to the plaintext logical block before storing it on the storage media.

This standard improves on IEEE Std 1619-2007 by defining *wide-block* encryption algorithms. This means that they act on the whole logical block at once, and each bit on the input plaintext influences every bit of the output ciphertext (and vice versa for decryption). In particular, this standard specifies the EME2-AES and the XCB-AES wide-block encryption algorithms.

Wide-block encryption better hides plaintext statistics and provides better protection than the narrow-block encryption, defined in IEEE Std 1619-2007, against attacks that involve traffic analysis and/or manipulations of ciphertext on the raw storage media.

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IEEE Standard for Wide-Block Encryption for Shared Storage Media

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1. Overview

1.1 Scope

This standard specifies an architecture for encryption of data in random access storage devices, oriented toward applications that benefit from wide encryption-block sizes of 512 bytes and above.

1.2 Purpose

This standard specifies an architecture for media security and enabling components. Wide encryption blocks are well suited to environments where the attacker has repeated access to cryptographic communication or ciphertext, or is able to perform traffic analysis of data access patterns. The standard is oriented toward fixed-size encryption blocks without data expansion, but anticipates an optional data expansion mode to resist attacks involving data tampering.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

NIST Federal Information Processing Standard 197 (FIPS 197), Advanced Encryption Standard (AES). November 2001.¹

NIST Special Publication 800-38A (NIST SP 800-38A), Recommendation for Block Cipher Modes of Operation—Methods and Techniques.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.²

associated data: Data that is associated with the plaintext, but that does not need to be encrypted. The associated data input should characterize the plaintext. In other algorithms for encryption of data at rest, the associated data is often referred to as *tweak value*.

encryption with associated data (EAD): A cryptographic algorithm that consists of an encryption procedure used to encrypt a plaintext and the associated data and a secret key, and a decryption procedure used to decrypt a ciphertext with the same associated data and secret key.

3.2 Keywords

can: A keyword indicating a capability (*can* equals *is able to*).

required: *See: shall.*

may: A keyword indicating a course of action permissible within the limits of this standard (*may* equals *is permitted to*).

must: A keyword used only to describe an unavoidable situation that does not constitute a requirement for compliance to this standard.

shall: A keyword indicating a mandatory requirement strictly to be followed in order to conform to this standard and from which no deviation is permitted (*shall* equals *is required to*).

shall not: A phrase indicating an absolute prohibition of this standard.

should: A keyword indicating that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required; or that (in the negative form) a certain course of action is deprecated but not prohibited (*should* equals *is recommended to*).

¹ NIST publications are available from the National Institute of Standards and Technology, NIST Public Inquiries, NIST, 100 Bureau Drive, Stop 3460, Gaithersburg, MD, 20899-3460, USA (www.nist.gov).

² *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

3.3 Acronyms and abbreviations

AES	Advanced Encryption Standard (see NIST FIPS 197 ³)
CTR	counter (as in AES counter mode of operation)
FIPS	Federal Information Processing Standard
GF	Galois Field (see Menezes et al. [B4] ⁴)
LBA	logical block address
GCM	Galois/Counter Mode of authenticated encryption

4. Mathematical conventions

This standard uses decimal, binary, and hexadecimal numbers. For clarity, decimal numbers generally represent counts, and binary or hexadecimal numbers describe bit patterns or raw binary data.

Binary numbers are represented by a string of one or more binary digits, followed by the subscript 2. For example, the decimal number 26 is represented as 00011010₂ in binary.

Hexadecimal numbers are represented by a string of one or more hexadecimal digits, prefixed by the string “0x.” For example, the decimal number 135 is represented as 0x87 in hexadecimal.

The number of bits in a bit string X is denoted as $\#X$.

The procedures used in this standard are as follows:

- AES-Enc(K, X), the AES block cipher encryption (see NIST FIPS 197), returns the encryption of the input X with the key K .
- AES-Dec(K, X), the AES block cipher decryption, returns the decryption of the input X with the key K .
- mult-by-alpha(X), the multiplication-by-alpha of a 16-byte value $X \in \text{GF}(2^{128})$ by a primitive element α in the field $\text{GF}(2^{128})$, defined in 5.2.1.
- $X \cdot Y$, the multiplication over the field $\text{GF}(2^{128})$ of two elements $X, Y \in \text{GF}(2^{128})$, defined in 5.3.3.
- $X \oplus Y$, the addition of two elements $X, Y \in \text{GF}(2^{128})$ that is equivalent to the bitwise exclusive-or operation.
- bitlength(X) returns an 8-byte string containing the non-negative integer describing the number of bits in the input X , with the most significant bit first and the least significant bit last. The expression 0^n denotes a string of n zero bits, and $A|B$ denotes the concatenation of two bit strings A and B .
- bytelength(X) returns as an integer the number of bytes in the input X .
- msb _{t} (X) returns the initial t bits of the input X . Bit strings are indexed starting from the most significant bit, so that bit zero of X is the most significant bit. $X[a:b]$ denotes the substring of X from the a th bit through the b th.

³ Information on references can be found in Clause 2.

⁴ The numbers in brackets correspond to those of the bibliography in Annex A.

5. Wide-block encryption algorithms

5.1 Encryption with associated data

5.1.1 Data units and associated data

This standard specifies length-preserving encryption with associated data (EAD) algorithms that are suitable for the encryption of data at rest. An EAD algorithm consists of an encryption procedure and a decryption procedure. The encryption procedure accepts three inputs as follows:

- Secret key
- Plaintext
- Associated data

It returns a single ciphertext value. Each of these inputs is a byte string.

The security of these procedures depends on the secret key consisting of random or pseudo-random data that is unpredictable to the adversary. Each EAD algorithm accepts a key of a fixed length, but different algorithms may have keys of different lengths.

The plaintext input contains the data to be encrypted. Plaintext is divided into data units that, within a particular key scope, may have different lengths. An EAD algorithm defines the range of admissible plaintext lengths. A compliant implementation should keep the size of the data units the same within a key scope. If an implementation allows variable-length data units within a key scope, then the implementation's design should be such that it is able to unambiguously determine the length of each data unit without using data that is potentially under the control of an adversary. A compliant implementation shall use distinct associated data for distinct data units.

The associated data input contains data that is associated with the plaintext, but that does not need to be encrypted. The choice of data for this input is described in more detail as follows. Within a particular key scope, associated data units may have different lengths.

The ciphertext returned by the encryption procedure is the same length as the plaintext.

The decryption procedure accepts three inputs as follows:

- Secret key
- Ciphertext
- Associated data value

It returns a single plaintext value. The decryption procedure is the reverse of the encryption procedure; more specifically, if the encryption of the plaintext P with the key K and the associated data A results in the ciphertext C , then the decryption of C with the key K and the associated data A results in the plaintext P .

A conforming implementation shall include in the associated data only information that is available, in plaintext form, at the time of encryption and the time of decryption.

The associated data input shall uniquely identify the plaintext. This is because whenever the same plaintext is encrypted two different times using the same key but with distinct associated data values, the result is

two distinct ciphertext values. Thus the use of distinct associated data values hides the equality of the plaintexts from an attacker.

5.1.2 Using EAD to protect a string of data blocks

An EAD may be used to protect a string of data blocks, such as those in a data-storage disk. In this application, the associated data input to the encryption and decryption procedure should contain the logical index of the block on which the procedure is acting. When this information is included in the associated data, cases in which two distinct data blocks contain identical plaintext values are hidden from an adversary. Figure 1 shows an example of how an EAD performs encryption and decryption.

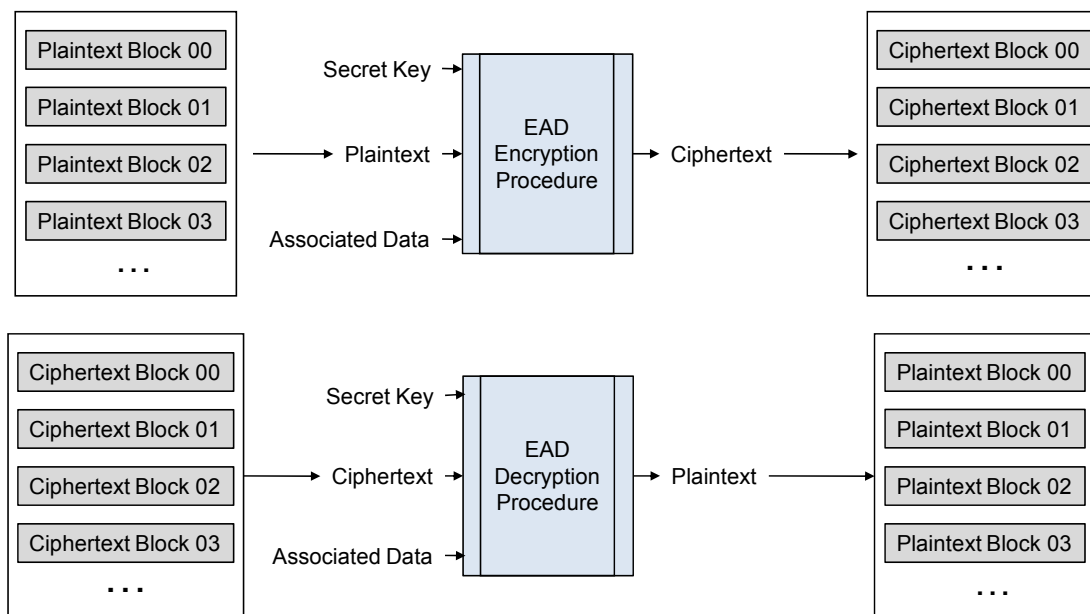


Figure 1—EAD encryption and decryption of a block device

If multiple disks are being protected with a single secret key, then the associated data input should contain both the logical index of the block and an additional distinguishing parameter that is unique to each of the disks. When this information is included in the associated data, cases in which two distinct data blocks on different disks contain identical plaintext values are hidden from an adversary.

5.2 EME2-AES algorithm

5.2.1 The mult-by-alpha procedure

The encryption and decryption procedures described in the following subclauses use a mult-by-alpha(X) procedure that multiplies a 16-byte value X by a primitive element α in the field $\text{GF}(2^{128})$. The input value is first converted into a byte string $X[i]$, $i = 0, 1, \dots, 15$, where $X[0]$ is the first byte of the byte string.

The multiplication by alpha is defined in Table 1 or by a mathematically equivalent procedure.

Table 1—The mult-by-alpha(X) procedure

```
// compute mult-by-alpha(X), where X is a 16-byte value
//
// X[i] denotes the ith byte of X, and indexing starts at 0
//
// i is an integer used in loops
//
// Y[i] denotes the ith byte of the output Y, and indexing starts at 0

1. for i = 0 to 15 do
2.   Y[i] = 2*X[i] mod 256
3.   if (i>0 and X[i-1]>127) then Y[i]=Y[i]+1
4. end-for
5. if (X[15] > 127) then Y[0] = Y[0]  $\oplus$  0x87
6. return Y
```

Conceptually, the procedure is a left shift of each byte by one bit with carry propagating from one byte to the next. Also, if the 15th (last) byte shift results in a carry, a special value (hexadecimal 0x87) is xor'ed into the first byte. This value is derived from the modulus of the Galois Field (polynomial $x^{128}+x^7+x^2+x+1$).

5.2.2 EME2-AES encryption

Equation (1) describes the EME2-AES encryption procedure:

$$C = \text{EME2-AES-Enc}(Key, T, P) \quad (1)$$

where

Key is the 48- or 64-byte EME2-AES key

T is the associated data, of arbitrary byte length (zero or more bytes)

P is the plaintext, of length 16 bytes or more

C is the ciphertext resulting from the operation, of the same byte-length as P

The input to the EME2-AES encryption procedure is parsed as follows:

- The key is partitioned into three fields, $Key = K_{AD} \mid K_{ECB} \mid K_{AES}$, with K_{AD} (the associated data key) consisting of the first 16 bytes, K_{ECB} (the ECB pass key) consisting of the following 16 bytes, and K_{AES} (the AES encryption/decryption key) consisting of the remaining 16 or 32 bytes.

- If not empty, the associated data T is partitioned into a sequence of blocks $T = T_1 | T_2 | \dots | T_r$, where each of the blocks $T_1, T_2, \dots, T_{r-1}$ is of length exactly 16 bytes, and T_r is of length between 1 and 16 bytes.
- The plaintext P is partitioned into a sequence of blocks $P = P_1 | P_2 | \dots | P_m$, where each of the blocks $P_1, P_2, \dots, P_{m-1}$ is of length exactly 16 bytes, and P_m is of length between 1 and 16 bytes.

As part of the ciphertext computation, the associated data T are processed by the sequence of steps in Table 2 or by a mathematically equivalent procedure.

Table 2—The function H for processing the associated data T

```
// Function H(KAES, KAD, T = (T1 | ... | Tr-1 | Tr) ) :
1. if bytlength(T) == 0 then
2.   T_star = AES-Enc(KAES, KAD)
3. else
4.   KAD = mult-by-alpha(KAD)
5.   for j = 1 to r-1
6.     TTj = AES-Enc(KAES, KAD ⊕ Tj) ⊕ KAD
7.     KAD = mult-by-alpha(KAD)
8.   next
9.   if bytlength(Tr) < 16 then
10.    Tr = Tr | 0x80 | 0x00 | ... // pad Tr to 16 bytes, 0x80 followed by 0's
11.    KAD = mult-by-alpha(KAD)
12.   endif
13.  TTr = AES-Enc(KAES, KAD ⊕ Tr) ⊕ KAD
14.  T_star = TT1 ⊕ TT2 ⊕ ... ⊕ TTr
15. endif
16. return T_star // return the 16 byte value T_star
```

A conforming implementation shall compute the ciphertext by executing the sequence of steps in Table 3 or a mathematically equivalent procedure.

Table 3—The EME2-AES encryption procedure

```
// EME2-AES-Enc( $K_{AES}$ ,  $K_{ECB}$ ,  $K_{AD}$ ,  $T$ ,  $P = (P_1 \mid \dots \mid P_{m-1} \mid P_m)$ ):
1.  $T\_star = H(K_{AES}, K_{AD}, T)$  // Process the associated data
2. if bytelength( $P_m$ ) == 16 then
3.   lastFull = m
4. else
5.   lastFull = m-1
6.    $PPP_m = P_m \mid 0x80 \mid 0x00 \mid \dots$  // Pad  $P_m$  to 16 bytes, 0x80 followed by 0's
7. endif

// First ECB pass
8.  $L = K_{ECB}$ 
9. for j = 1 to lastFull
10.   $PPP_j = \text{AES-Enc}(K_{AES}, L \oplus P_j)$ 
11.   $L = \text{mult-by-alpha}(L)$ 
12. next

// Intermediate mixing
13.  $MP = PPP_1 \oplus PPP_2 \oplus \dots \oplus PPP_m \oplus T\_star$ 
14. if bytelength( $P_m$ ) < 16 then
15.   $MM = \text{AES-Enc}(K_{AES}, MP)$ 
16.   $MC = MC_1 = \text{AES-Enc}(K_{AES}, MM)$ 
17. else
18.   $MC = MC_1 = \text{AES-Enc}(K_{AES}, MP)$ 
19. endif
20.  $M = M_1 = MP \oplus MC$ 
21. for j = 2 to lastFull
22.  if (j-1 mod 128 > 0) then // use the current mask M
23.     $M = \text{mult-by-alpha}(M)$ 
24.     $CCC_j = PPP_j \oplus M$ 
25.  else // calculate a new mask M
26.     $MP = PPP_j \oplus M_1$ 
27.     $MC = \text{AES-Enc}(K_{AES}, MP)$ 
28.     $M = MP \oplus MC$ 
29.     $CCC_j = MC \oplus M_1$ 
30.  endif
31. next
32. if lastFull < m then
33.   $C_m = P_m \oplus (MM \text{ truncated to bytelength}(P_m) \text{ bytes})$ 
34.   $CCC_m = C_m \mid 0x80 \mid 0x00 \mid \dots$  // Pad  $C_m$  to 16 bytes, 0x80 followed by 0's
35. endif
36.  $CCC_1 = MC_1 \oplus CCC_2 \oplus \dots \oplus CCC_m \oplus T\_star$ 

// Second ECB Pass
37.  $L = K_{ECB}$ 
38. for j = 1 to lastFull
39.   $C_j = \text{AES-Enc}(K_{AES}, CCC_j) \oplus L$ 
40.   $L = \text{mult-by-alpha}(L)$ 
41. next

42. return  $C = (C_1 \mid \dots \mid C_{m-1} \mid C_m)$ 
```

An illustration of the EME2-AES encryption procedure (for plaintext of 130 full blocks and one partial block) is provided in Figure 2.

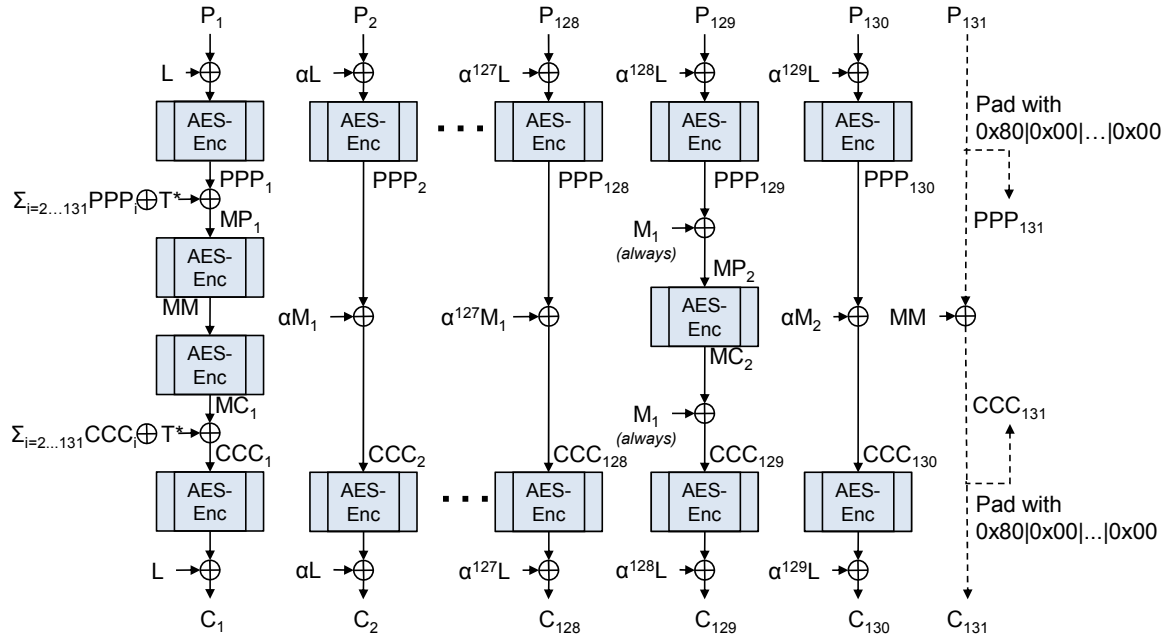


Figure 2—An illustration of EME2-AES encryption

In Figure 2, each AES-Enc block has a Key input that is not shown. T^* is computed from the associated data using the function H from Table 2, and the M_i 's are computed as $M_i = MP_i \text{ xor } MC_i$.

5.2.3 EME2-AES decryption

Equation (2) describes the EME2-AES decryption procedure:

$$P = \text{EME2-AES-Dec}(Key, T, C) \quad (2)$$

where

- Key is the 48- or 64-byte EME2-AES key
- T is the associated data, of arbitrary byte length (zero or more bytes)
- C is the ciphertext, of length 16 bytes or more
- P is the plaintext resulting from the operation, of the same byte-length as C

The input to the EME2-AES decryption procedure is parsed as follows:

- The key is partitioned into three fields, $Key = K_{AD} \mid K_{ECB} \mid K_{AES}$, with K_{AD} (the associated data key) consisting of the first 16 bytes, K_{ECB} (the ECB pass key) consisting of the following 16 bytes, and K_{AES} (the AES encryption/decryption key) consisting of the remaining 16 or 32 bytes.
- If not empty, the associated data is partitioned into a sequence of blocks $T = T_1 \mid T_2 \mid \dots \mid T_r$, where each of the blocks $T_1, T_2, \dots, T_{r-1}$ is of length exactly 16 bytes, and T_r is of length between 1 and 16 bytes.
- The ciphertext C is partitioned into a sequence of blocks $C = C_1 \mid C_2 \mid \dots \mid C_m$, where each of the blocks $C_1, C_2, \dots, C_{m-1}$ is of length exactly 16 bytes, and C_m is of length between 1 and 16 bytes.

A conforming implementation shall compute the plaintext by executing the sequence of steps in Table 4 or a mathematically equivalent procedure.

NOTE—The only difference between the encryption and decryption procedures is that all the AES-Enc calls in Table 3 are replaced in Table 4 by calls to AES-Dec. The function H is defined in Table 2.⁵

⁵ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

Table 4—The EME2-AES decryption procedure

```
// EME2-AES-Dec( $K_{AES}$ ,  $K_{ECB}$ ,  $K_{AD}$ ,  $T$ ,  $C = (C_1 \mid \dots \mid C_{m-1} \mid C_m)$  ):
1.  $T\_star = H(K_{AES}, K_{AD}, T)$  // Process the associated data
2. if bytelength( $C_m$ ) == 16 then
3.   lastFull = m
4. else
5.   lastFull = m-1
6.    $CCC_m = C_m \mid 0x80 \mid 0x00 \mid \dots$  // Pad  $C_m$  to 16 bytes, 0x80 followed by 0's
7. endif

// First ECB pass
8.  $L = K_{ECB}$ 
9. for j = 1 to lastFull
10.   $CCC_j = AES\text{-}Enc(K_{AES}, L \oplus C_j)$ 
11.   $L = \text{mult-by-alpha}(L)$ 
12. next

// Intermediate mixing
13.  $MC = CCC_1 \oplus CCC_2 \oplus \dots \oplus CCC_m \oplus T\_star$ 
14. if bytelength( $C_m$ ) < 16 then
15.   $MM = AES\text{-}Dec(K_{AES}, MC)$ 
16.   $MP = MP_1 = AES\text{-}Dec(K_{AES}, MM)$ 
17. else
18.   $MP = MP_1 = AES\text{-}Dec(K_{AES}, MC)$ 
19. endif
20.  $M = M_1 = MP \oplus MC$ 
21. for j = 2 to lastFull
22.   if (j-1 mod 128 > 0) then // use the current mask M
23.     $M = \text{mult-by-alpha}(M)$ 
24.     $PPP_j = CCC_j \oplus M$ 
25.   else // calculate a new mask M
26.     $MC = CCC_j \oplus M_1$ 
27.     $MP = AES\text{-}Dec(K_{AES}, MC)$ 
28.     $M = MP \oplus MC$ 
29.     $PPP_j = MP \oplus M_1$ 
30.   endif
31. next
32. if lastFull < m then
33.   $P_m = C_m \oplus (MM \text{ truncated to bytelength}(C_m) \text{ bytes})$ 
34.   $PPP_m = P_m \mid 0x80 \mid 0x00 \mid \dots$  // Pad  $P_m$  to 16 bytes, 0x80 followed by 0's
35. endif
36.  $PPP_1 = MP_1 \oplus PPP_2 \oplus \dots \oplus PPP_m \oplus T\_star$ 

// Second ECB Pass
37.  $L = K_{ECB}$ 
38. for j = 1 to lastFull
39.   $P_j = AES\text{-}Dec(K_{AES}, PPP_j) \oplus L$ 
40.   $L = \text{mult-by-alpha}(L)$ 
41. next
42. return  $P = (P_1 \dots P_{m-1} P_m)$ 
```

5.3 XCB-AES algorithm

5.3.1 Overview of XCB-AES

The XCB-AES algorithm use the AES block cipher encryption procedures AES-Enc and AES-Dec, as well as the hash function h and the pseudorandom function c . The variables H , K_e , K_d , and K_c are derived from K , essentially by running the AES-Enc encryption procedure in CTR mode (see NIST SP 800-38A). A conforming implementation may store these values between computation of encryption and decryption procedures, in order to trade off storage and computational load.

5.3.2 The function c

Let k be the size of the key fed to the AES procedure (either 16 or 32 bytes).

The function c : $\{0, 255\}^k \times \{0, 255\}^{16} \rightarrow \{0, 255\}^l$, where the output length l (in bytes) is bounded by $0 \leq l \leq 2^{36}$, generates an arbitrary-length output by running the AES-Enc procedure in CTR mode, using its 16-byte input as the initial counter value. Its definition is as follows:

$$c(K, W, l) = \text{AES-Enc}(K, W) \mid \text{AES-Enc}(K, \text{incr}(W)) \mid \dots \mid \text{msb}_t(\text{AES-Enc}(K, \text{incr}^{n-l}(W)))$$

where the output length l is indicated as an explicit parameter for clarity; $n = \lceil l / 16 \rceil$ is the number of 16-byte blocks in the output, and $t = l \bmod 16$ is the number of bytes in the trailing block.

Here the function incr : $\{0, 255\}^{16} \rightarrow \{0, 255\}^{16}$ is the increment operation that is used to generate successive counter values. This function treats the rightmost 4 bytes of its argument as a non-negative integer with the least significant byte on the right, and increments this value modulo 2^{32} . More formally,

$$\text{incr}(X) = X[0:95] \mid (X[96:127] + 1 \bmod 2^{32})$$

where bit strings are implicitly converted into integers.

5.3.3 Multiplication in $\text{GF}(2^{128})$

The multiplication operation of two 16-byte values $X, Y \in \text{GF}(2^{128})$ is mathematically equivalent to an operation on bit vectors. The result $Z = X \cdot Y$ is also an element of $\text{GF}(2^{128})$. The input values are first converted into a byte string $X[i]$, $i = 0, 1, \dots, 15$, where the most significant byte is $X[0]$, and the least significant byte is $X[15]$.

The multiplication in $\text{GF}(2^{128})$ operation is defined in Table 5 or by a mathematically equivalent procedure:

Table 5—The multiplication in GF(2¹²⁸) procedure

```
// mult-GF(X, Y)

// compute Z = X * Y, where X, Y, Z are elements of GF(2128) using a
// byte based algorithm
//
// here A[i] denotes the ith byte of A, and indexing starts at 0
//
// i and j are integers used in loops
// mask, b, and msb are unsigned integers

/* initialize z to the all-zero element */
7. for i = 0 to 15
8.   z[i] = 0
9. next

10. for i=0 to 15 /* loop over bytes of y */
11.   mask = 128
12.   while mask > 0 /* loop over bits in byte */
13.     /* if masked bit is set, add in terms from x */
14.     b = y[i] & mask
15.     if b != 0
16.       for j=0 to 15
17.         set z[j] to z[j] ^ x[j]
18.       next
19.     endif
20.     mask = mask / 2;
21.     /* now execute LFSR shift on x */
22.     set msb to x[15] & 0x01
23.     for j=15 down to 1
24.       set b to x[j-1] & 0x01
25.       set x[j] to (x[j] / 2) + b * 128
26.     next
27.     set x[0] to x[0] / 2
28.     if msb == 1
29.       set x[0] to x[0] ^ 0xe1
30.     endif
31.   endwhile
32. next
33. return z
```

NOTE—In Table 5, the multiplication operation uses the special element $R = 11100001_2 0^{120} (0xe1 \mid 0x00 \mid \dots \mid 0x00)$.

5.3.4 The procedures h_1 and h_2

The procedures h_1 and h_2 are defined in terms of the underlying hash function h as follows:

$$h_1(H, Z, B) = h(H, 0^{128} \mid Z, B \mid 0^{\text{padlen1}(\#B)})$$

$$h_2(H, Z, B) = h(H, Z \mid 0^{128}, B \mid 0^{\text{padlen2}(\#B)} \mid \text{bitlength}(Z \mid 0^{128}) \mid \text{bitlength}(B))$$

The procedure $\text{padlen2}(x)$ returns the integer between 0 and 127, inclusive, that when added to x is a multiple of 128. The procedure $\text{padlen1}(x)$ returns $\text{padlen2}(x) + 128$. Equation (3) and Equation (4) express these statements mathematically:

$$\text{padlen2}(x) = 128 * \text{ceil}(x/128) - x \quad (3)$$

$$\text{padlen1}(x) = 128 * (1 + \text{ceil}(x/128)) - x = 128 + \text{padlen2}(x) \quad (4)$$

where $\text{ceil}(x)$ is the smallest integer that is larger than or equal to x .

The procedure $h : \{0, 1\}^{128} \times \{0, 1\}^a \times \{0, 1\}^c \rightarrow \{0, 1\}^{128}$ is defined by $h(H, A, C) = X_{m+n+1}$, where a and c are within the interval $[128, 2^{39}]$, m is the number of 16-byte blocks in A , n is the number of 16-byte blocks in C , and the variables $X_i \in \{0, 1\}^{128}$ for $i = 0, \dots, m+n+1$ are defined as follows:

$$\begin{aligned} X_i &= 0 & \text{for } i = 0 \\ X_i &= (X_{i-1} \oplus A_i) \cdot H & \text{for } i = 1, \dots, m-1 \\ X_i &= (X_{m-1} \oplus A_m) \cdot H & \text{for } i = m \\ X_i &= (X_{i-1} \oplus C_{i-m}) \cdot H & \text{for } i = m+1, \dots, m+n-1 \\ X_i &= (X_{m+n-1} \oplus C_n) \cdot H & \text{for } i = m+n \\ X_i &= (X_{m+n} \oplus (\text{bitlength}(A) \mid \text{bitlength}(C))) \cdot H & \text{for } i = m+n+1 \end{aligned}$$

Let A_i denote the 16-byte substring $A[128*(i-1): 128*i-1]$, and let C_i denote $C[128*(i-1): 128*i-1]$. In other words, A_i and C_i are the i th blocks of A and C , respectively, if those bit strings are decomposed into 16-byte blocks (the last A_i and C_i blocks are padded with 0s, if shorter than 16 bytes).

NOTE—This procedure is identical to the universal hash function that is used as a component of the Galois/Counter Mode (GCM) of Operation (see NIST SP 800-38D [B5]). It is equivalent to the procedure used in Step 5 of Algorithm 4 of that specification, but please note that it is different than GHASH as defined in that document.

5.3.5 XCB-AES encryption

The XCB-AES encryption procedure for an m -bit block P is modeled with Equation (5):

$$CT \leftarrow \text{XCB-AES-Enc}(K, P, Z) \quad (5)$$

where

K is the 16- or 32-byte XCB-AES key
 P is the plaintext of m bits where $m \in [128, 2^{32}]$, and m is a multiple of 8
 Z is the value of the associated data, of arbitrary byte length (zero or more bytes)
 CT is the ciphertext resulting from the operation, of the same length as P

A conforming implementation shall compute the ciphertext by executing the following steps or a mathematically equivalent procedure (see Figure 3):

$$\begin{aligned} H &\leftarrow \text{AES-Enc}(K, 0^{128}) \\ K_e &\leftarrow \text{msb}_k(\text{AES-Enc}(K, 0^{125}|001_2) \parallel \text{AES-Enc}(K, 0^{125}|010_2)) \\ K_d &\leftarrow \text{msb}_k(\text{AES-Enc}(K, 0^{125}|011_2) \parallel \text{AES-Enc}(K, 0^{125}|100_2)) \\ K_c &\leftarrow \text{msb}_k(\text{AES-Enc}(K, 0^{125}|101_2) \parallel \text{AES-Enc}(K, 0^{125}|110_2)) \\ A &\leftarrow P[m-128: m-1] \\ B &\leftarrow P[0: m-127] \\ C &\leftarrow \text{AES-Enc}(K_e, A) \\ D &\leftarrow C \oplus h_1(H, Z, B) \\ E &\leftarrow B \oplus c(K_c, D, \#B) \\ F &\leftarrow D \oplus h_2(H, Z, E) \\ G &\leftarrow \text{AES-Dec}(K_d, F) \\ CT &\leftarrow E \parallel G \end{aligned}$$

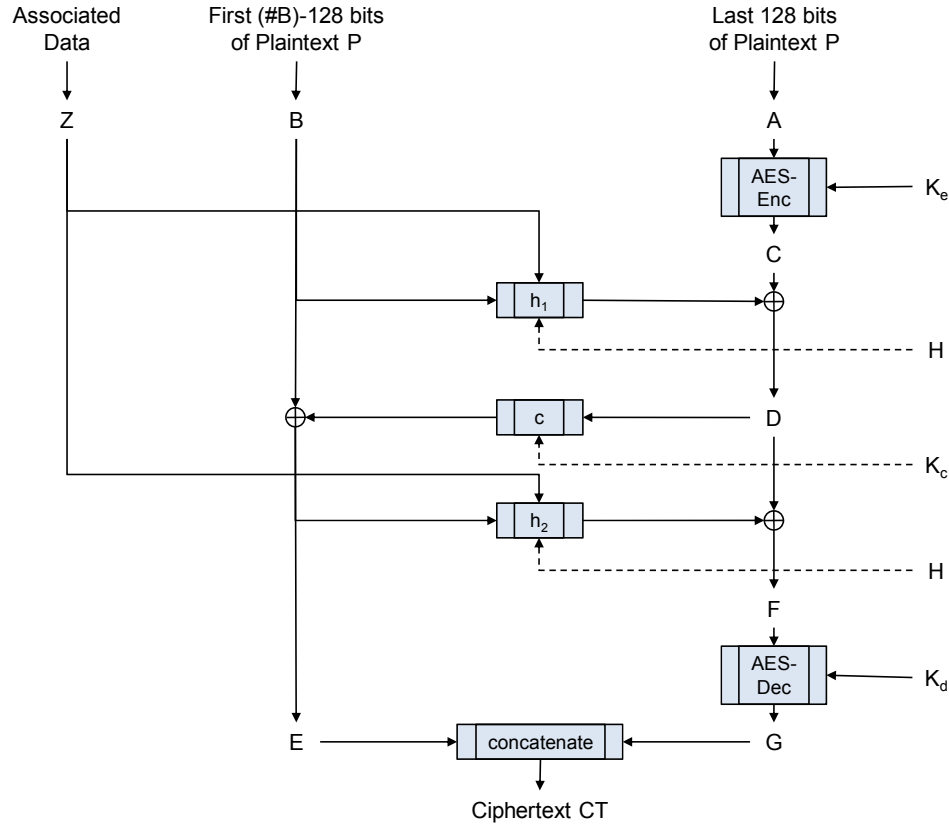


Figure 3—An illustration of XCB-AES encryption

5.3.6 XCB-AES decryption

The XCB-AES decryption procedure for an m -bit block CT is modeled with Equation (6):

$$P \leftarrow \text{XCB-AES-Dec}(K, CT, Z) \quad (6)$$

where

K is the 16- or 32-byte XCB-AES key

CT is the ciphertext of m bits where $m \in [128, 2^{32}]$, and m is a multiple of 8

Z is the associated data, of arbitrary byte length (zero or more bytes)

P is the plaintext resulting from the operation, of the same length as CT

A conforming implementation shall compute the plaintext by executing the following sequence of steps or a mathematically equivalent procedure (see Figure 4):

$$\begin{aligned} H &\leftarrow \text{AES-Enc}(K, 0^{128}) \\ K_e &\leftarrow \text{msb}_k(\text{AES-Enc}(K, 0^{125}|001_2) \parallel \text{AES-Enc}(K, 0^{125}|010_2)) \\ K_d &\leftarrow \text{msb}_k(\text{AES-Enc}(K, 0^{125}|011_2) \parallel \text{AES-Enc}(K, 0^{125}|100_2)) \\ K_c &\leftarrow \text{msb}_k(\text{AES-Enc}(K, 0^{125}|101_2) \parallel \text{AES-Enc}(K, 0^{125}|110_2)) \\ G &\leftarrow CT[m-128: m-1] \\ E &\leftarrow CT[0: m-127] \\ F &\leftarrow \text{AES-Enc}(K_d, G) \\ D &\leftarrow F \oplus h_2(H, Z, E) \\ B &\leftarrow E \oplus c(K_c, D, \#E) \\ C &\leftarrow D \oplus h_1(H, Z, B) \\ A &\leftarrow \text{AES-Dec}(K_e, C) \\ P &\leftarrow B \parallel A \end{aligned}$$

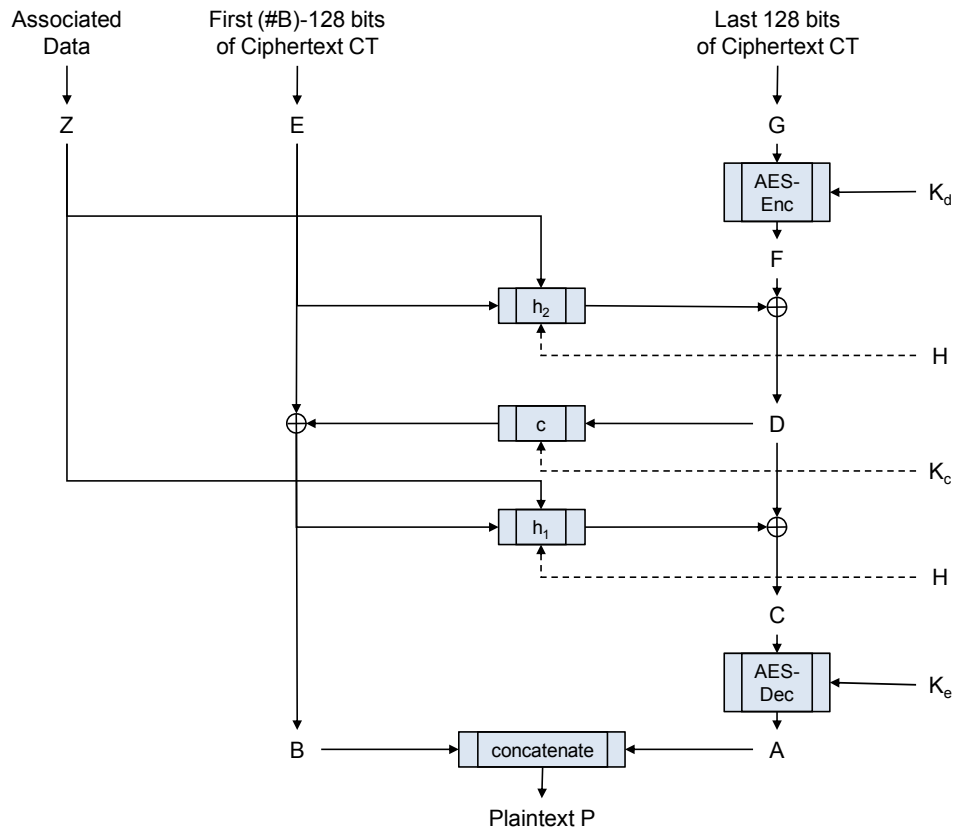


Figure 4—An illustration of XCB-AES decryption

6. Compliance

The EME2-AES encryption and decryption procedures described in 5.2.2 and 5.2.3 use AES as the basic building block with a key of either 48 or 64 bytes. EME2-AES-128 uses a 48-byte key and EME2-AES-256 uses a 64-byte key.

The XCB-AES encryption and decryption procedures described in 5.3.3 and 5.3.6 use AES as the basic building block with a key of either 16 or 32 bytes. XCB-AES-128 uses a 16-byte key and XCB-AES-256 uses a 32-byte key.

An implementation may claim compliance with this standard if it fulfills all the requirements for either the encryption or decryption procedures or both of at least one of the following algorithms:

- EME2-AES-128
- EME2-AES-256
- XCB-AES-128
- XCB-AES-256