

Network Working Group
Internet-Draft
Intended status: Standards Track
Expires: August 18, 2014

D. McGrew
J. Foley
Cisco Systems
K. Paterson
Royal Holloway, University of
London
February 14, 2014

**Authenticated Encryption with AES-CBC and HMAC-SHA
draft-mcgrew-aead-aes-cbc-hmac-sha2-04.txt**

Abstract

This document specifies algorithms for authenticated encryption with associated data (AEAD) that are based on the composition of the Advanced Encryption Standard (AES) in the Cipher Block Chaining (CBC) mode of operation for encryption, and the HMAC-SHA message authentication code (MAC).

These are randomized encryption algorithms, and thus are suitable for use with applications that cannot provide distinct nonces to each invocation of the AEAD encrypt operation.

Status of this Memo

This Internet-Draft is submitted in full conformance with the provisions of [BCP 78](#) and [BCP 79](#).

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at <http://datatracker.ietf.org/drafts/current/>.

Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress."

This Internet-Draft will expire on August 18, 2014.

Copyright Notice

Copyright (c) 2014 IETF Trust and the persons identified as the document authors. All rights reserved.

This document is subject to [BCP 78](#) and the IETF Trust's Legal Provisions Relating to IETF Documents

(<http://trustee.ietf.org/license-info>) in effect on the date of publication of this document. Please review these documents carefully, as they describe your rights and restrictions with respect to this document. Code Components extracted from this document must include Simplified BSD License text as described in Section 4.e of the Trust Legal Provisions and are provided without warranty as described in the Simplified BSD License.

Table of Contents

1.	Introduction	3
1.1.	History	3
1.2.	Conventions Used In This Document	4
2.	CBC-HMAC algorithms	5
2.1.	Encryption	5
2.2.	Decryption	7
2.3.	Length	8
2.4.	AEAD_AES_128_CBC_HMAC_SHA_256	8
2.5.	AEAD_AES_192_CBC_HMAC_SHA_384	9
2.6.	AEAD_AES_256_CBC_HMAC_SHA_384	9
2.7.	AEAD_AES_256_CBC_HMAC_SHA_512	10
2.8.	Summary	10
3.	Randomness Requirements	11
4.	Rationale	12
5.	Test Cases	14
5.1.	AEAD_AES_128_CBC_HMAC_SHA256	14
5.2.	AEAD_AES_192_CBC_HMAC_SHA384	15
5.3.	AEAD_AES_256_CBC_HMAC_SHA384	17
5.4.	AEAD_AES_256_CBC_HMAC_SHA512	18
6.	Security Considerations	20
7.	Acknowledgements	22
8.	References	23
8.1.	Normative References	23
8.2.	Informative References	23
Appendix A.	CBC Encryption and Decryption	26
Appendix B.	Alternative Interface for Legacy Encoding	28
	Authors' Addresses	29

1. Introduction

Authenticated Encryption (AE) [BN00] is a form of encryption that, in addition to providing confidentiality for the plaintext that is encrypted, provides a way to check its integrity and authenticity. This combination of features can, when properly implemented, provide security against adversaries who have access to full decryption capabilities for ciphertexts of their choice, and access to full encryption capabilities for plaintexts of their choice. The strong form of security provided by AE is known to be robust against a large class of adversaries for general purpose applications of AE, including applications such as securing network communications over untrusted networks. The strong security properties of AE stand in contrast to the known weaknesses of "encryption only" forms of encryption, see [B96][YHR04] [DP07] for examples.

Authenticated encryption with Associated Data, or AEAD [R02], adds the ability to check the integrity and authenticity of some associated data (sometimes called "additional authenticated data") for which confidentiality is not required (or is not desirable). While many approaches to building AEAD schemes are known, a particularly simple, well-understood, and cryptographically strong method is to employ an "Encrypt-then-MAC" construction. This document defines new AEAD algorithms of this general type, using the interface defined in [RFC5116], based on the Advanced Encryption Standard (AES) [FIPS197] in the Cipher Block Chaining (CBC) mode of operation [SP800-38] and HMAC using the Secure Hash Algorithm (SHA) [FIPS186-2], with security levels of 128, 192, and 256 bits.

Comments on this version are requested and should be forwarded to the IRTF Crypto Forum Research Group (CFRG). An earlier version of this document benefited from some review from that group.

1.1. History

This subsection describes the revision history of this Internet Draft. It should be removed by the RFC Editor before publication as an RFC.

The changes of version 02 from version 01 are:

- Added test cases for each of the five operational modes.

- Added John as a coauthor.

- Adds a legacy-style interface in [Appendix B](#).

The changes of version 01 from version 00 are:

MIN_LEN_A and associated logic was eliminated.

Padding String (PS) typo corrected in [Section 2.1](#).

Decryption Step 3 refers to the appropriate step in the encryption process.

Random IV min-entropy clarified in [Section 3](#).

HMAC keys are now the same size as the truncated output (128 or 256 bits). Previously, the HMAC keys were the same size as the full hash output (256, 384, or 512 bits).

An algorithm based on the combination of AES-256 and HMAC-SHA-384 has been added, for compatibility with [draft-burgin-kerberos-aes-cbc-hmac-sha2](#).

The test cases in the previous version are no longer valid, and thus have been removed. New test cases have been computed (and the authors thank John Foley for this contribution) but have not been included, pending confirmation from a second, independent implementation.

[1.2](#). Conventions Used In This Document

We use the following notational conventions.

CBC-ENC(X,P) denotes the CBC encryption of P using the cipher with the key X

MAC(Y, M) denotes the application of the Message Authentication Code (MAC) to the message M, using the key Y

The concatenation of two octet strings A and B is denoted as
A || B

len(X) denotes the number of bits in the string X, expressed as an unsigned integer in network byte order.

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [[RFC2119](#)].

2. CBC-HMAC algorithms

This section defines CBC-HMAC, an algorithm based on the the encrypt-then-MAC method defined in Section 4.3 of [BN00]. That method constructs a randomized AEAD algorithm out of a randomized cipher, such as a block cipher mode of operation that uses a random initialization vector, and a MAC.

[Section 2.1](#) and [Section 2.2](#) define the CBC-HMAC encryption and decryption algorithms, without specifying the particular block cipher or hash function to be used. [Section 2.4](#), [Section 2.5](#), and [Section 2.7](#) define instances of CBC-HMAC that specify those details.

2.1. Encryption

We briefly recall the encryption interface defined in [Section 2 of \[RFC5116\]](#). The AEAD encryption algorithm takes as input four octet strings: a secret key K, a plaintext P, associated data A, and a nonce N. An authenticated ciphertext value is provided as output. The data in the plaintext are encrypted and authenticated, and the associated data are authenticated, but not encrypted. The key MUST be generated in a way that is uniformly random or pseudorandom; guidance on random sources is provided in [\[RFC4086\]](#).

In CBC-HMAC, the nonce N MUST be a zero-length string; a nonce is not needed and is not used (see [Section 4](#) for further background).

The CBC-HMAC encryption process is as follows, or uses an equivalent set of steps:

1. The secondary keys MAC_KEY and ENC_KEY are generated from the input key K as follows. Each of these two keys is an octet string.

MAC_KEY consists of the initial MAC_KEY_LEN octets of K, in order.

ENC_KEY consists of the final ENC_KEY_LEN octets of K, in order.

Here we denote the number of octets in the MAC_KEY as MAC_KEY_LEN, and the number of octets in ENC_KEY as ENC_KEY_LEN; the values of these parameters are specified by the AEAD algorithms (in [Section 2.4](#) and [Section 2.5](#)). The number of octets in the input key K is the sum of MAC_KEY_LEN and ENC_KEY_LEN. When generating the secondary keys from K, MAC_KEY and ENC_KEY MUST NOT overlap.

2. Prior to CBC encryption, the plaintext P is padded by appending a padding string PS to that data, to ensure that $\text{len}(P \parallel PS)$ is a multiple of 128, as is needed for the CBC operation. The value of PS is as follows:

$PS = 01$	if $\text{len}(P) \bmod 128 = 120,$
$PS = 0202$	if $\text{len}(P) \bmod 128 = 112,$
$PS = 030303$	if $\text{len}(P) \bmod 128 = 104,$
$PS = 04040404$	if $\text{len}(P) \bmod 128 = 96,$
$PS = 0505050505$	if $\text{len}(P) \bmod 128 = 88,$
$PS = 060606060606$	if $\text{len}(P) \bmod 128 = 80,$
$PS = 07070707070707$	if $\text{len}(P) \bmod 128 = 72,$
$PS = 0808080808080808$	if $\text{len}(P) \bmod 128 = 64,$
$PS = 0909090909090909$	if $\text{len}(P) \bmod 128 = 56,$
$PS = 0A0A0A0A0A0A0A0A0A$	if $\text{len}(P) \bmod 128 = 48,$
$PS = 0B0B0B0B0B0B0B0B0B0B$	if $\text{len}(P) \bmod 128 = 40,$
$PS = 0C0C0C0C0C0C0C0C0C0C$	if $\text{len}(P) \bmod 128 = 32,$
$PS = 0D0D0D0D0D0D0D0D0D0D0D$	if $\text{len}(P) \bmod 128 = 24,$
$PS = 0E0E0E0E0E0E0E0E0E0E0E$	if $\text{len}(P) \bmod 128 = 16,$
$PS = 0F0F0F0F0F0F0F0F0F0F0F0F$	if $\text{len}(P) \bmod 128 = 8,$
$PS = 10101010101010101010101010101010$	if $\text{len}(P) \bmod 128 = 0.$

Note that padding **MUST** be added to the plaintext; if the number of bits in P is a multiple of 128, then 128 bits of padding will be added.

3. The plaintext and appended padding $P \parallel PS$ is CBC encrypted using ENC_KEY as the key, as described in [Appendix A](#). We denote the ciphertext output from this step as S .
4. The octet string AL is equal to the number of bits in A expressed as a 64-bit unsigned integer in network byte order.
5. A message authentication tag T is computed by applying HMAC [\[RFC2104\]](#) to the following data, in order:

the associated data A ,

the ciphertext S computed in the previous step, and

the octet string AL defined above.

The string MAC_KEY is used as the MAC key. We denote the output of the MAC computed in this step as T .

6. The AEAD Ciphertext consists of the string S , with the string T appended to it. This Ciphertext is returned as the output of the AEAD encryption operation.

The encryption process can be illustrated as follows. Here P, A, and C denote the AEAD plaintext, associated data, and ciphertext, respectively.

MAC_KEY = initial MAC_KEY_LEN bytes of K

ENC_KEY = final ENC_KEY_LEN bytes of K

S = CBC-ENC(ENC_KEY, P || PS),

T = MAC(MAC_KEY, A || S || AL),

C = S || T.

2.2. Decryption

The authenticated decryption operation has four inputs: K, N, and A, as defined above, and the Ciphertext C. As discussed above, N is an empty string in AES-CBC and is not used below. It has only a single output, either a plaintext value P or a special symbol FAIL that indicates that the inputs are not authentic. The authenticated decryption algorithm takes is as follows, or uses an equivalent set of steps:

1. The secondary keys MAC_KEY and ENC_KEY are generated from the input key K as in Step 1 of [Section 2.1](#).
2. The final T_LEN octets are stripped from C. Here T_LEN denotes the number of octets in the MAC, which is a fixed parameter of the AEAD algorithm. We denote the initial octets of C as S, and denote the final T_LEN octets as T.
3. The integrity and authenticity of A and C are checked by computing HMAC with the inputs as in Step 6 of [Section 2.1](#). The value T, from the previous step, is compared to the HMAC output, using a comparison routine that takes constant time to execute. If those values are identical, then A and C are considered valid, and the processing continues. Otherwise, all of the data used in the MAC validation are discarded, and the AEAD decryption operation returns an indication that it failed, and the operation halts.
4. The value S is CBC decrypted, as described in [Appendix A](#), using the value ENC_KEY as the decryption key.
5. The padding string is stripped from the resulting plaintext. Note that the length of PS can be inferred from the value of the final octet of P || PS, if that value is between 01 and 10

(hexadecimal). If the final octet has a value outside that range, then all of the data used in the processing of the message is zeroized and discarded, and the AEAD decryption operation returns an indication that it failed, and the operation halts.

6. The plaintext value is returned.

2.3. Length

The length of the ciphertext can be inferred from that of the plaintext. The number L of octets in the ciphertext is given by

$$L = 16 * (\text{floor}(M / 16) + 2)$$

where M denotes the number of octets in the plaintext, and the function `floor()` rounds its argument down to the nearest integer. This fact is useful to applications that need to reserve space for a ciphertext within a message or data structure.

2.4. AEAD_AES_128_CBC_HMAC_SHA_256

This algorithm is randomized; each invocation of the encrypt operation makes use of a random value (the IV described in [Appendix A](#)). It is based on the CBC-HMAC algorithm detailed above, and uses the HMAC message authentication code [[RFC2104](#)] with the SHA-256 hash function [[FIPS186-2](#)] to provide message authentication, with the HMAC output truncated to 128 bits, corresponding to the HMAC-SHA-256-128 algorithm defined in [[RFC4868](#)]. For encryption, it uses the Advanced Encryption Standard (AES) [[FIPS197](#)] block cipher in CBC mode.

The input key K is 32 octets long.

ENC_KEY_LEN is 16 octets.

The SHA-256 hash algorithm is used in HMAC. MAC_KEY_LEN is 16 octets. The HMAC-SHA-256 output is truncated to T_LEN=16 octets, by stripping off the final 16 octets. Test cases for HMAC-SHA-256 are provided in [[RFC4231](#)].

The lengths of the inputs are restricted as follows:

K_LEN is 32 octets,

P_MAX is $2^{64} - 1$ octets,

A_MAX is $2^{64} - 1$ octets,

N_MIN and N_MAX are zero octets,

C_MAX is $2^{64} + 47$ octets.

2.5. AEAD_AES_192_CBC_HMAC_SHA_384

AEAD_AES_192_CBC_HMAC_SHA_384 is based on AEAD_AES_128_CBC_HMAC_SHA_256, but with the following differences:

AES-192 is used instead of AES-128.

SHA-384 is used in HMAC instead of SHA-256.

ENC_KEY_LEN is 24 octets.

MAC_KEY_LEN is 24 octets.

The length of the input key K is 48 octets.

The HMAC-SHA-384 value is truncated to T_LEN=24 octets instead of 16 octets.

The input length restrictions are as for AEAD_AES_CBC_128_HMAC_SHA_256.

2.6. AEAD_AES_256_CBC_HMAC_SHA_384

AEAD_AES_256_CBC_HMAC_SHA_384 is based on AEAD_AES_128_CBC_HMAC_SHA_256, but with the following differences:

AES-256 is used instead of AES-128.

SHA-384 is used in HMAC instead of SHA-256.

ENC_KEY_LEN is 32 octets.

MAC_KEY_LEN is 24 octets.

The length of the input key K is 56 octets.

The HMAC-SHA-384 value is truncated to T_LEN=24 octets instead of 16 octets.

The input length restrictions are as for AEAD_AES_CBC_128_HMAC_SHA_256.

2.7. AEAD_AES_256_CBC_HMAC_SHA_512

AEAD_AES_256_CBC_HMAC_SHA_512 is based on AEAD_AES_128_CBC_HMAC_SHA_256, but with the following differences:

AES-256 is used instead of AES-128.

SHA-512 is used in HMAC instead of SHA-256.

ENC_KEY_LEN is 32 octets.

MAC_KEY_LEN is 32 octets.

The length of the input key K is 64 octets.

The HMAC-SHA-512 value is truncated to T_LEN=32 octets instead of 16 octets.

The input length restrictions are as for AEAD_AES_CBC_128_HMAC_SHA_256.

2.8. Summary

The parameters of the CBC-HMAC algorithms are summarized in the following table.

algorithm	ENC_KEY_LEN	MAC_KEY_LEN	T_LEN
AEAD_AES_128_CBC_HMAC_SHA_256	16	16	16
AEAD_AES_192_CBC_HMAC_SHA_384	24	24	24
AEAD_AES_256_CBC_HMAC_SHA_384	32	24	24
AEAD_AES_256_CBC_HMAC_SHA_512	32	32	32

3. Randomness Requirements

Each IV MUST be unpredictable to the adversary. It MAY be chosen uniformly at random, in which case it SHOULD have min-entropy within one bit of `len(IV)`. Alternatively, it MAY be generated pseudorandomly, using any method that provides the same level of security as the block cipher in use. However, if a pseudorandom method is used, that method MUST NOT make use of `ENC_KEY` or `MAC_KEY`.

4. Rationale

The CBC-HMAC AEAD algorithms defined in this note are intended to be useful in the following applications:

systems that have the CBC and HMAC algorithms available, but do not have dedicated AEAD algorithms such as GCM or CCM [[RFC5116](#)],

scenarios in which AEAD is useful, but it is undesirable to have the application maintain a deterministic nonce; see [Section 4 of \[RFC5116\]](#) for more background,

new systems, such as JSON Cryptography and W3C Web Crypto, which can omit unauthenticated symmetric encryption altogether by providing CBC and HMAC through an AEAD interface.

These algorithms are not intended to replace existing uses of AES-CBC and HMAC, except in those circumstances where the existing use is not sufficiently secure or sufficiently general-purpose.

The algorithms in this note truncate the HMAC output to half of the size of the output of the underlying hash function. This size is the recommended minimum (see [Section 5 of \[RFC2104\]](#)), and this parameter choice has withstood the test of time.

The length of the associated data input A is included in the HMAC input to ensure that the encrypter and the decrypter have the same understanding of that length. Because of this, an attacker cannot trick the receiver into interpreting the initial bytes of C as the final bytes of A, or vice-versa.

The padding method used in this note is based on that of Privacy Enhanced Mail (PEM) and the Public Key Cryptography Standards (PKCS), because it is implemented in many environments.

The encrypt-then-MAC method is used because of its better security properties. It would be possible to define AEAD algorithms based on the MAC-encode-encrypt (MEE) method that is used by the Transport Layer Security (TLS) protocol [[RFC5246](#)]. That alternative would provide more code-sharing opportunities for an implementation that is co-resident with a TLS implementation. It is possible (but tricky) to implement MEE in a way that provides good security, as was shown in [[PRS11](#)]. But its negatives outweigh its positives; its security is inadequate for some parameter choices, and it has proven to be very difficult to implement in a way that resists padding oracle and related timing attacks [[V02](#)] [[CHVV03](#)] [[M04](#)] [[DP10](#)] [[AP12](#)]. For future uses of CBC and HMAC, it is better to use encrypt-then-MAC.

This note uses HMAC-SHA-2 because it is widely deployed, it is mandated in newer standards, and because SHA1 is being deprecated. It has been recently announced that the SHA-3 standard will be based on KECCAK, but this note does not incorporate that hash function. To do so would be to speculate on the final form of the SHA-3 standard. In addition, while the use of KECCAK as a hash function is straightforward, there are multiple options for its use in authenticated encryption. The focus of this note is the definition of AEAD algorithms based on currently used cryptographic mechanisms, so SHA-3 is out of scope.

5. Test Cases

5.1. AEAD_AES_128_CBC_HMAC_SHA256

K = 00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
 10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f

MAC_KEY = 00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f

ENC_KEY = 10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f

P = 41 20 63 69 70 68 65 72 20 73 79 73 74 65 6d 20
 6d 75 73 74 20 6e 6f 74 20 62 65 20 72 65 71 75
 69 72 65 64 20 74 6f 20 62 65 20 73 65 63 72 65
 74 2c 20 61 6e 64 20 69 74 20 6d 75 73 74 20 62
 65 20 61 62 6c 65 20 74 6f 20 66 61 6c 6c 20 69
 6e 74 6f 20 74 68 65 20 68 61 6e 64 73 20 6f 66
 20 74 68 65 20 65 6e 65 6d 79 20 77 69 74 68 6f
 75 74 20 69 6e 63 6f 6e 76 65 6e 69 65 6e 63 65

IV = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04

A = 54 68 65 20 73 65 63 6f 6e 64 20 70 72 69 6e 63
 69 70 6c 65 20 6f 66 20 41 75 67 75 73 74 65 20
 4b 65 72 63 6b 68 6f 66 66 73

PS = 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10

AL = 00 00 00 00 00 00 01 50

S = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
 c8 0e df a3 2d df 39 d5 ef 00 c0 b4 68 83 42 79
 a2 e4 6a 1b 80 49 f7 92 f7 6b fe 54 b9 03 a9 c9
 a9 4a c9 b4 7a d2 65 5c 5f 10 f9 ae f7 14 27 e2
 fc 6f 9b 3f 39 9a 22 14 89 f1 63 62 c7 03 23 36
 09 d4 5a c6 98 64 e3 32 1c f8 29 35 ac 40 96 c8
 6e 13 33 14 c5 40 19 e8 ca 79 80 df a4 b9 cf 1b
 38 4c 48 6f 3a 54 c5 10 78 15 8e e5 d7 9d e5 9f
 bd 34 d8 48 b3 d6 95 50 a6 76 46 34 44 27 ad e5
 4b 88 51 ff b5 98 f7 f8 00 74 b9 47 3c 82 e2 db

T = 65 2c 3f a3 6b 0a 7c 5b 32 19 fa b3 a3 0b c1 c4

C = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
 c8 0e df a3 2d df 39 d5 ef 00 c0 b4 68 83 42 79
 a2 e4 6a 1b 80 49 f7 92 f7 6b fe 54 b9 03 a9 c9
 a9 4a c9 b4 7a d2 65 5c 5f 10 f9 ae f7 14 27 e2
 fc 6f 9b 3f 39 9a 22 14 89 f1 63 62 c7 03 23 36
 09 d4 5a c6 98 64 e3 32 1c f8 29 35 ac 40 96 c8
 6e 13 33 14 c5 40 19 e8 ca 79 80 df a4 b9 cf 1b
 38 4c 48 6f 3a 54 c5 10 78 15 8e e5 d7 9d e5 9f
 bd 34 d8 48 b3 d6 95 50 a6 76 46 34 44 27 ad e5
 4b 88 51 ff b5 98 f7 f8 00 74 b9 47 3c 82 e2 db
 65 2c 3f a3 6b 0a 7c 5b 32 19 fa b3 a3 0b c1 c4

5.2. AEAD_AES_192_CBC_HMAC_SHA384

K = 00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
 10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f
 20 21 22 23 24 25 26 27 28 29 2a 2b 2c 2d 2e 2f

MAC_KEY = 00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
 10 11 12 13 14 15 16 17

ENC_KEY = 18 19 1a 1b 1c 1d 1e 1f 20 21 22 23 24 25 26 27
 28 29 2a 2b 2c 2d 2e 2f

P = 41 20 63 69 70 68 65 72 20 73 79 73 74 65 6d 20
 6d 75 73 74 20 6e 6f 74 20 62 65 20 72 65 71 75
 69 72 65 64 20 74 6f 20 62 65 20 73 65 63 72 65
 74 2c 20 61 6e 64 20 69 74 20 6d 75 73 74 20 62
 65 20 61 62 6c 65 20 74 6f 20 66 61 6c 6c 20 69
 6e 74 6f 20 74 68 65 20 68 61 6e 64 73 20 6f 66
 20 74 68 65 20 65 6e 65 6d 79 20 77 69 74 68 6f
 75 74 20 69 6e 63 6f 6e 76 65 6e 69 65 6e 63 65

IV = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04

A = 54 68 65 20 73 65 63 6f 6e 64 20 70 72 69 6e 63
 69 70 6c 65 20 6f 66 20 41 75 67 75 73 74 65 20
 4b 65 72 63 6b 68 6f 66 66 73

PS = 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10

AL = 00 00 00 00 00 00 01 50

S = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
 ea 65 da 6b 59 e6 1e db 41 9b e6 2d 19 71 2a e5
 d3 03 ee b5 00 52 d0 df d6 69 7f 77 22 4c 8e db
 00 0d 27 9b dc 14 c1 07 26 54 bd 30 94 42 30 c6
 57 be d4 ca 0c 9f 4a 84 66 f2 2b 22 6d 17 46 21
 4b f8 cf c2 40 0a dd 9f 51 26 e4 79 66 3f c9 0b
 3b ed 78 7a 2f 0f fc bf 39 04 be 2a 64 1d 5c 21
 05 bf e5 91 ba e2 3b 1d 74 49 e5 32 ee f6 0a 9a
 c8 bb 6c 6b 01 d3 5d 49 78 7b cd 57 ef 48 49 27
 f2 80 ad c9 1a c0 c4 e7 9c 7b 11 ef c6 00 54 e3

T = 84 90 ac 0e 58 94 9b fe 51 87 5d 73 3f 93 ac 20
 75 16 80 39 cc c7 33 d7

C = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
 ea 65 da 6b 59 e6 1e db 41 9b e6 2d 19 71 2a e5
 d3 03 ee b5 00 52 d0 df d6 69 7f 77 22 4c 8e db
 00 0d 27 9b dc 14 c1 07 26 54 bd 30 94 42 30 c6
 57 be d4 ca 0c 9f 4a 84 66 f2 2b 22 6d 17 46 21
 4b f8 cf c2 40 0a dd 9f 51 26 e4 79 66 3f c9 0b
 3b ed 78 7a 2f 0f fc bf 39 04 be 2a 64 1d 5c 21
 05 bf e5 91 ba e2 3b 1d 74 49 e5 32 ee f6 0a 9a
 c8 bb 6c 6b 01 d3 5d 49 78 7b cd 57 ef 48 49 27
 f2 80 ad c9 1a c0 c4 e7 9c 7b 11 ef c6 00 54 e3
 84 90 ac 0e 58 94 9b fe 51 87 5d 73 3f 93 ac 20
 75 16 80 39 cc c7 33 d7

5.3. AEAD_AES_256_CBC_HMAC_SHA384

K = 00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
 10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f
 20 21 22 23 24 25 26 27 28 29 2a 2b 2c 2d 2e 2f
 30 31 32 33 34 35 36 37

MAC_KEY = 00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
 10 11 12 13 14 15 16 17

ENC_KEY = 18 19 1a 1b 1c 1d 1e 1f 20 21 22 23 24 25 26 27
 28 29 2a 2b 2c 2d 2e 2f 30 31 32 33 34 35 36 37

P = 41 20 63 69 70 68 65 72 20 73 79 73 74 65 6d 20
 6d 75 73 74 20 6e 6f 74 20 62 65 20 72 65 71 75
 69 72 65 64 20 74 6f 20 62 65 20 73 65 63 72 65
 74 2c 20 61 6e 64 20 69 74 20 6d 75 73 74 20 62
 65 20 61 62 6c 65 20 74 6f 20 66 61 6c 6c 20 69
 6e 74 6f 20 74 68 65 20 68 61 6e 64 73 20 6f 66
 20 74 68 65 20 65 6e 65 6d 79 20 77 69 74 68 6f
 75 74 20 69 6e 63 6f 6e 76 65 6e 69 65 6e 63 65

IV = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04

A = 54 68 65 20 73 65 63 6f 6e 64 20 70 72 69 6e 63
 69 70 6c 65 20 6f 66 20 41 75 67 75 73 74 65 20
 4b 65 72 63 6b 68 6f 66 66 73

PS = 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10

AL = 00 00 00 00 00 00 01 50

S = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
 89 31 29 b0 f4 ee 9e b1 8d 75 ed a6 f2 aa a9 f3
 60 7c 98 c4 ba 04 44 d3 41 62 17 0d 89 61 88 4e
 58 f2 7d 4a 35 a5 e3 e3 23 4a a9 94 04 f3 27 f5
 c2 d7 8e 98 6e 57 49 85 8b 88 bc dd c2 ba 05 21
 8f 19 51 12 d6 ad 48 fa 3b 1e 89 aa 7f 20 d5 96
 68 2f 10 b3 64 8d 3b b0 c9 83 c3 18 5f 59 e3 6d
 28 f6 47 c1 c1 39 88 de 8e a0 d8 21 19 8c 15 09
 77 e2 8c a7 68 08 0b c7 8c 35 fa ed 69 d8 c0 b7
 d9 f5 06 23 21 98 a4 89 a1 a6 ae 03 a3 19 fb 30

T = dd 13 1d 05 ab 34 67 dd 05 6f 8e 88 2b ad 70 63
 7f 1e 9a 54 1d 9c 23 e7


```

C =      1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
        89 31 29 b0 f4 ee 9e b1 8d 75 ed a6 f2 aa a9 f3
        60 7c 98 c4 ba 04 44 d3 41 62 17 0d 89 61 88 4e
        58 f2 7d 4a 35 a5 e3 e3 23 4a a9 94 04 f3 27 f5
        c2 d7 8e 98 6e 57 49 85 8b 88 bc dd c2 ba 05 21
        8f 19 51 12 d6 ad 48 fa 3b 1e 89 aa 7f 20 d5 96
        68 2f 10 b3 64 8d 3b b0 c9 83 c3 18 5f 59 e3 6d
        28 f6 47 c1 c1 39 88 de 8e a0 d8 21 19 8c 15 09
        77 e2 8c a7 68 08 0b c7 8c 35 fa ed 69 d8 c0 b7
        d9 f5 06 23 21 98 a4 89 a1 a6 ae 03 a3 19 fb 30
        dd 13 1d 05 ab 34 67 dd 05 6f 8e 88 2b ad 70 63
        7f 1e 9a 54 1d 9c 23 e7

```

5.4. AEAD_AES_256_CBC_HMAC_SHA512

```

K =      00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
        10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f
        20 21 22 23 24 25 26 27 28 29 2a 2b 2c 2d 2e 2f
        30 31 32 33 34 35 36 37 38 39 3a 3b 3c 3d 3e 3f

```

```

MAC_KEY = 00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
        10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f

```

```

ENC_KEY = 20 21 22 23 24 25 26 27 28 29 2a 2b 2c 2d 2e 2f
        30 31 32 33 34 35 36 37 38 39 3a 3b 3c 3d 3e 3f

```

```

P =      41 20 63 69 70 68 65 72 20 73 79 73 74 65 6d 20
        6d 75 73 74 20 6e 6f 74 20 62 65 20 72 65 71 75
        69 72 65 64 20 74 6f 20 62 65 20 73 65 63 72 65
        74 2c 20 61 6e 64 20 69 74 20 6d 75 73 74 20 62
        65 20 61 62 6c 65 20 74 6f 20 66 61 6c 6c 20 69
        6e 74 6f 20 74 68 65 20 68 61 6e 64 73 20 6f 66
        20 74 68 65 20 65 6e 65 6d 79 20 77 69 74 68 6f
        75 74 20 69 6e 63 6f 6e 76 65 6e 69 65 6e 63 65

```

```

IV =      1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04

```

```

A =      54 68 65 20 73 65 63 6f 6e 64 20 70 72 69 6e 63
        69 70 6c 65 20 6f 66 20 41 75 67 75 73 74 65 20
        4b 65 72 63 6b 68 6f 66 66 73

```

```

PS =      10 10 10 10 10 10 10 10 10 10 10 10 10 10 10

```

```

AL =      00 00 00 00 00 00 01 50

```


S = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
 4a ff aa ad b7 8c 31 c5 da 4b 1b 59 0d 10 ff bd
 3d d8 d5 d3 02 42 35 26 91 2d a0 37 ec bc c7 bd
 82 2c 30 1d d6 7c 37 3b cc b5 84 ad 3e 92 79 c2
 e6 d1 2a 13 74 b7 7f 07 75 53 df 82 94 10 44 6b
 36 eb d9 70 66 29 6a e6 42 7e a7 5c 2e 08 46 a1
 1a 09 cc f5 37 0d c8 0b fe cb ad 28 c7 3f 09 b3
 a3 b7 5e 66 2a 25 94 41 0a e4 96 b2 e2 e6 60 9e
 31 e6 e0 2c c8 37 f0 53 d2 1f 37 ff 4f 51 95 0b
 be 26 38 d0 9d d7 a4 93 09 30 80 6d 07 03 b1 f6

T = 4d d3 b4 c0 88 a7 f4 5c 21 68 39 64 5b 20 12 bf
 2e 62 69 a8 c5 6a 81 6d bc 1b 26 77 61 95 5b c5

C = 1a f3 8c 2d c2 b9 6f fd d8 66 94 09 23 41 bc 04
 4a ff aa ad b7 8c 31 c5 da 4b 1b 59 0d 10 ff bd
 3d d8 d5 d3 02 42 35 26 91 2d a0 37 ec bc c7 bd
 82 2c 30 1d d6 7c 37 3b cc b5 84 ad 3e 92 79 c2
 e6 d1 2a 13 74 b7 7f 07 75 53 df 82 94 10 44 6b
 36 eb d9 70 66 29 6a e6 42 7e a7 5c 2e 08 46 a1
 1a 09 cc f5 37 0d c8 0b fe cb ad 28 c7 3f 09 b3
 a3 b7 5e 66 2a 25 94 41 0a e4 96 b2 e2 e6 60 9e
 31 e6 e0 2c c8 37 f0 53 d2 1f 37 ff 4f 51 95 0b
 be 26 38 d0 9d d7 a4 93 09 30 80 6d 07 03 b1 f6
 4d d3 b4 c0 88 a7 f4 5c 21 68 39 64 5b 20 12 bf
 2e 62 69 a8 c5 6a 81 6d bc 1b 26 77 61 95 5b c5

6. Security Considerations

The algorithms defined in this document use the generic composition of CBC encryption with HMAC authentication, with the encrypt-then-MAC method defined in Section 4.3 of [BN00]. This method has sound and well-understood security properties; for details, please see that reference. Note that HMAC is a good pseudorandom function and is "strongly unforgeable", and thus meets all of the security goals of that reference.

Implementations of the encryption and decryption algorithms should avoid side channels that would leak information about the secret key. To avoid timing channels, the processing time should be independent of the secret key. The Encrypt-then-MAC construction used in this note has some inherent strength against timing attacks because, during the decryption operation, the authentication check is computed before the plaintext padding is processed. However, the security of the algorithm still relies on the absence of timing channels in both CBC and HMAC. Additionally, comparison between the authentication tag T and the HMAC output should be done using a constant-time operation.

During the decryption process, the inputs A and C are mapped into the input of the HMAC algorithm. It is essential for security that each possible input to the MAC algorithm corresponds unambiguously to exactly one pair (A, C) of possible inputs. The fact that this property holds can be verified as follows. The HMAC input is $X = A || C || \text{len}(A)$. Let (A,C) and (A',C') denote two distinct input pairs, in which either 1) $A \neq A'$ and $C = C'$, 2) $C \neq C'$ and $A = A'$, or 3) both inequalities hold. We also let $X' = A' || C' || \text{len}(A')$. In cases 1 and 2, $X \neq X'$ follows immediately. In case 3, if $\text{len}(A) \neq \text{len}(A')$, then $X \neq X'$ directly. If $\text{len}(A) = \text{len}(A')$, then $X \neq X'$ follows from the fact that the initial $\text{len}(A)$ bits of X and X' must be distinct.

There are security benefits to providing both confidentiality and authentication in a single atomic operation, as done in this note. This tight binding prevents subtle attacks such as the padding oracle attack.

As with any block cipher mode of operation, the security of AES-CBC degrades as the amount of data that is process increases. Each fixed key value SHOULD NOT be used to protect more than 2^{64} bytes of data. This limit ensures that the AES-CBC algorithm will stay under the birthday bound, i.e. because of the limit, it is unlikely that there will be two AES plaintext inputs that are equal. (If this event occurs, information about the colliding plaintexts is leaked, so it is desirable to bound the amount of plaintext processed in order to

make it unlikely.)

7. Acknowledgements

Thanks are due to Matt Miller for his constructive feedback, Kelly Burgin, Michael Peck, and Mike Jones for their suggestions and help, and Jim Schaad, Rob Napier, James Manger, and David Jacobson for their excellent review and suggestions.

8. References

8.1. Normative References

- [FIPS186-2] "FIPS 180-2: Secure Hash Standard," Federal Information Processing Standard (FIPS) <http://www.itl.nist.gov/fipspubs/fip180-1.htm>.
- [FIPS197] "FIPS 197: Advanced Encryption Standard (AES)," Federal Information Processing Standard (FIPS) <http://www.itl.nist.gov/fipspubs/fip197.htm>.
- [RFC2104] Krawczyk, H., Bellare, M., and R. Canetti, "HMAC: Keyed-Hashing for Message Authentication", [RFC 2104](#), February 1997.
- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", [BCP 14](#), [RFC 2119](#), March 1997.
- [RFC4231] Nystrom, M., "Identifiers and Test Vectors for HMAC-SHA-224, HMAC-SHA-256, HMAC-SHA-384, and HMAC-SHA-512", [RFC 4231](#), December 2005.
- [RFC4868] Kelly, S. and S. Frankel, "Using HMAC-SHA-256, HMAC-SHA-384, and HMAC-SHA-512 with IPsec", [RFC 4868](#), May 2007.
- [RFC5116] McGrew, D., "An Interface and Algorithms for Authenticated Encryption", [RFC 5116](#), January 2008.

8.2. Informative References

- [AP12] Paterson, K. and N. AlFardan, "Plaintext-Recovery Attacks Against Datagram TLS", Network and Distributed System Security Symposium (NDSS) 2012 <http://www.isg.rhul.ac.uk/~kp/dtls.pdf>, 2012.
- [B96] Bellare, S., "Problem areas for the IP security protocols", Proceedings of the Sixth Usenix Unix Security Symposium <https://www.cs.columbia.edu/~smb/papers/badesp.pdf>, 1996.
- [BN00] "Authenticated encryption: Relations among notions and analysis of the generic composition paradigm", Proceedings of ASIACRYPT 2000, Springer-Verlag, LNCS 1976, pp. 531-545 <http://www-cse.ucsd.edu/users/mihir/papers/oem.html>.
- [CHVV03] Vaudenay, S., Canvel, B., Hiltgen, A., and M. Vuagnoux,

- "Password Interception in a SSL/TLS Channel", CRYPT0 2003 <http://lasecwww.epfl.ch/pub/lasec/doc/CHVV03.ps>, 2003.
- [DP07] Paterson, K. and J. Degabriele, "Attacking the IPsec Standards in Encryption-only Configurations", IEEE Symposium on Privacy and Security <http://eprint.iacr.org/2007/125.pdf>, 2007.
- [DP10] Paterson, K. and J. Degabriele, "On the (in)security of IPsec in MAC-then-encrypt configurations.", ACM Conference on Computer and Communications Security (ACM CCS) 2010 <http://www.isg.rhul.ac.uk/~kp/CCSIPsecfinal.pdf>, 2010.
- [M04] Moeller, B., "Security of CBC Ciphersuites in SSL/TLS: Problems and Countermeasures", Web Page <http://www.openssl.org/~bodo/tls-cbc.txt>, 2004.
- [PRS11] Paterson, K., Ristenpart, T., and T. Shrimpton, "Tag Size Does Matter: Attacks and Proofs for the TLS Record Protocol", IEEE Symposium on Security and Privacy 2012 <http://www.isg.rhul.ac.uk/~kp/mee-comp.pdf>, January 2012.
- [R02] "Authenticated encryption with Associated-Data", Proceedings of the 2002 ACM Conference on Computer and Communication Security (CCS'02), pp. 98-107, ACM Press, 2002. <http://www.cs.ucdavis.edu/~rogaway/papers/ad.pdf>.
- [RFC4086] Eastlake, D., Schiller, J., and S. Crocker, "Randomness Requirements for Security", [BCP 106](#), [RFC 4086](#), June 2005.
- [RFC5246] Dierks, T. and E. Rescorla, "The Transport Layer Security (TLS) Protocol Version 1.2", [RFC 5246](#), August 2008.
- [SP800-38] Dworkin, M., "NIST Special Publication 800-38: Recommendation for Block Cipher Modes of Operation", U.S. National Institute of Standards and Technology <http://csrc.nist.gov/publications/nistpubs/800-38a/sp800-38a.pdf>.
- [V02] Vaudenay, S., "Security Flaws Induced by CBC Padding - Applications to SSL, IPSEC, WTLS", EUROCRYPT 2002 http://lasecwww.epfl.ch/php_code/publications/search.php?ref=Vau02a, 2002.
- [YHR04] Yu, T., Hartman, S., and K. Raeburn, "The Perils of

Unauthenticated Encryption: Kerberos Version 4", Network
and Distributed Security Symposium (NDSS)
2004 <http://web.mit.edu/tlyu/papers/krb4peril-ndss04.pdf>,
2004.

Appendix A. CBC Encryption and Decryption

The Cipher Block Chaining (CBC) mode of operation is defined in Section 6.2 of [SP800-38]. This section recalls how that mode works, for the convenience of the reader. The following notation is used:

K denotes the key of the underlying block cipher,

The function $CIPHER(K, P)$ denotes the encryption of the block P with the block cipher, where P contains exactly b bits,

The function $CIPHER-INV(K, C)$ denotes the decryption of the block C with the block cipher, where C contains exactly b bits; this is the inverse operation of $CIPHER()$, and $CIPHER-INV(K, CIPHER(K, P)) = P$ for all P and all K ,

P_1, P_2, \dots, P_n denotes the sequence of plaintext blocks, where each block contains exactly b bits,

$C_0, C_1, C_2, \dots, C_n$ denotes the sequence of ciphertext blocks, where each block contains exactly b bits,

P_i and C_i denote the i th blocks of the plaintext, and

IV denotes the initialization vector, which contains exactly b bits.

The CBC encryption operation (denoted as CBC-ENC) takes as input a sequence of n plaintext blocks and produces a sequence of $n + 1$ ciphertext blocks as follows:

```
IV = random
C_i = / IV                                if i=0,
      \ CIPHER(K, P_i XOR C_{i-1})      if i=1, 2, ... , n.
```

$CBC-ENC(K, P_1 || P_2 || \dots || P_n)$ returns the value $C_0 || C_1 || C_2 || \dots || C_n$. Note that the returned value is one block longer than the input value, and that $C_0 = IV$.

The IV MUST be generated using a uniformly random process, or a pseudorandom process with a cryptographic strength equivalent to that of the underlying block cipher; see [RFC4086] for background on random sources. It MUST NOT be predictable to an attacker; in particular, it MUST NOT be set to the value of any previous ciphertext blocks.

The CBC decryption operation (denoted as CBC-DEC) takes as input a sequence of m ciphertext blocks and produces a sequence of $m-1$

plaintext blocks as follows:

$$P_i = \text{CIPHER-INV}(K, C_i) \text{ XOR } C_{i-1} \quad \text{for } i=1, 2, \dots, n.$$

The initial block C_0 corresponds to the initialization vector.

[Appendix B](#). Alternative Interface for Legacy Encoding

In some scenarios, cryptographic data such as the ciphertext, initialization vector, and message authentication tag are encoded separately. To allow for the use of the algorithms defined in this document in such scenarios, this appendix describes an interface in which those data elements are discrete. New implementations SHOULD NOT use this interface, because it is incompatible with other authenticated encryption methods and is more complex; however, it MAY be useful in scenarios in which the separate encoding is already in use.

The alternative interface is as follows. The inputs to the encryption operation the same as those defined in [Section 2.1](#) (the secret key K, the plaintext P, the associated data A). The outputs of the encryption operation are:

- the initialization vector IV as defined in [Appendix A](#),

- the ciphertext C, as defined in [Appendix A](#), and

- the message authentication tag T, as defined in [Section 2.1](#).

The inputs to the decryption operation (in addition to K and A) are:

- the initialization vector IV as defined in [Appendix A](#),

- the ciphertext C as defined in [Appendix A](#), excluding the initial block C₀ (which is equal to the IV), and

- the message authentication tag T, as defined in [Section 2.1](#).

The output of the decryption operation are the same as that defined in [Section 2.2](#) (either a plaintext value P or a special symbol FAIL that indicates that the inputs are not authentic).

All processing other than the encoding and decoding of IV, C, and T is done as defined above. In particular, the IV is an output of the encryption operation, rather than an input.

Authors' Addresses

David McGrew
Cisco Systems
13600 Dulles Technology Drive
Herndon, VA 20171
US

Email: mcgrew@cisco.com

URI: <http://www.mindspring.com/~dmcgrew/dam.htm>

John Foley
Cisco Systems
7025-2 Kit Creek Road
Research Triangle Park, NC 14987
US

Email: foleyj@cisco.com

Kenny Paterson
Royal Holloway, University of London
TW20 0EX
Egham, Surrey TW20 0EX
UK

Phone: +44 1784 414393

Email: Kenny.Paterson@rhul.ac.uk

URI: <http://www.isg.rhul.ac.uk/~kp/>

