              Using Advanced Encryption Standard (AES) CCM Mode
                with IPsec Encapsulating Security Payload (ESP)

Status of This Memo

   This document specifies an Internet standards track protocol for the
   Internet community, and requests discussion and suggestions for
   improvements. Please refer to the current edition of the "Internet
   Official Protocol Standards" (STD 1) for the standardization state
   and status of this protocol. Distribution of this memo is unlimited.

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Abstract

   This document describes the use of Advanced Encryption Standard (AES)
   in Counter with CBC-MAC (CCM) Mode, with an explicit initialization
   vector (IV), as an IPsec Encapsulating Security Payload (ESP)
   mechanism to provide confidentiality, data origin authentication, and
   connectionless integrity.

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1. Introduction

   The Advanced Encryption Standard (AES) [AES] is a block cipher, and
   it can be used in many different modes. This document describes the
   use of AES in CCM (Counter with CBC-MAC) mode (AES CCM), with an
   explicit initialization vector (IV), as an IPsec Encapsulating
   Security Payload (ESP) [ESP] mechanism to provide confidentiality,
   data origin authentication, and connectionless integrity.

   This document does not provide an overview of IPsec. However,
   information about how the various components of IPsec and the way in
   which they collectively provide security services is available in
   [ARCH] and [ROAD].

1.1. Conventions Used in This Document

   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 [STDWORDS].

2. AES CCM Mode

   CCM is a generic authenticate-and-encrypt block cipher mode [CCM].
   In this specification, CCM is used with the AES [AES] block cipher.

   AES CCM has two parameters:

      M M indicates the size of the integrity check value (ICV). CCM
         defines values of 4, 6, 8, 10, 12, 14, and 16 octets; However,
         to maintain alignment and provide adequate security, only the
         values that are a multiple of four and are at least eight are
         permitted. Implementations MUST support M values of 8 octets
         and 16 octets, and implementations MAY support an M value of 12
         octets.

      L L indicates the size of the length field in octets. CCM
         defines values of L between 2 octets and 8 octets. This
         specification only supports L = 4. Implementations MUST
         support an L value of 4 octets, which accommodates a full
         Jumbogram [JUMBO]; however, the length includes all of the
         encrypted data, which also includes the ESP Padding, Pad
         Length, and Next Header fields.

There are four inputs to CCM originator processing:

    key
        A single key is used to calculate the ICV using CBC-MAC and to
        perform payload encryption using counter mode. AES supports
        key sizes of 128 bits, 192 bits, and 256 bits. The default key

        size is 128 bits, and implementations MUST support this key
        size. Implementations MAY also support key sizes of 192 bits
        and 256 bits.

    nonce
        The size of the nonce depends on the value selected for the
        parameter L. It is 15-L octets. Implementations MUST support
        a nonce of 11 octets. The construction of the nonce is
        described in Section 4.

    payload
        The payload of the ESP packet. The payload MUST NOT be longer
        than 4,294,967,295 octets, which is the maximum size of a
        Jumbogram [JUMBO]; however, the ESP Padding, Pad Length, and
        Next Header fields are also part of the payload.

    AAD
        CCM provides data integrity and data origin authentication for
        some data outside the payload. CCM does not allow additional
        authenticated data (AAD) to be longer than
        18,446,744,073,709,551,615 octets. The ICV is computed from
        the ESP header, Payload, and ESP trailer fields, which is
        significantly smaller than the CCM-imposed limit. The
        construction of the AAD described in Section 5.

AES CCM requires the encryptor to generate a unique per-packet value
and to communicate this value to the decryptor. This per-packet
value is one of the component parts of the nonce, and it is referred
to as the initialization vector (IV). The same IV and key
combination MUST NOT be used more than once. The encryptor can
generate the IV in any manner that ensures uniqueness. Common
approaches to IV generation include incrementing a counter for each
packet and linear feedback shift registers (LFSRs).

AES CCM employs counter mode for encryption. As with any stream
cipher, reuse of the same IV value with the same key is catastrophic.
An IV collision immediately leaks information about the plaintext in
both packets. For this reason, it is inappropriate to use this CCM
with statically configured keys. Extraordinary measures would be
needed to prevent reuse of an IV value with the static key across

power cycles. To be safe, implementations MUST use fresh keys with
AES CCM. The Internet Key Exchange (IKE) [IKE] protocol or IKEv2
[IKEv2] can be used to establish fresh keys.

3. ESP Payload

The ESP payload is composed of the IV followed by the ciphertext.
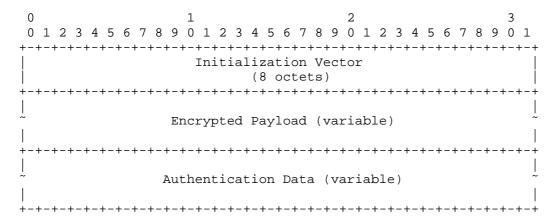The payload field, as defined in [ESP], is structured as shown in
Figure 1.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                   Initialization Vector                       |
|                        (8 octets)                             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
~               Encrypted Payload (variable)                    ~
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
~               Authentication Data (variable)                  ~
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

             Figure 1. ESP Payload Encrypted with AES CCM

3.1. Initialization Vector (IV)

The AES CCM IV field MUST be eight octets. The IV MUST be chosen by
the encryptor in a manner that ensures that the same IV value is used
only once for a given key. The encryptor can generate the IV in any
manner that ensures uniqueness. Common approaches to IV generation
include incrementing a counter for each packet and linear feedback
shift registers (LFSRs).

Including the IV in each packet ensures that the decryptor can
generate the key stream needed for decryption, even when some
datagrams are lost or reordered.

3.2. Encrypted Payload

The encrypted payload contains the ciphertext.

AES CCM mode does not require plaintext padding. However, ESP does
require padding to 32-bit word-align the authentication data. The
Padding, Pad Length, and Next Header fields MUST be concatenated

with the plaintext before performing encryption, as described in
[ESP]. When padding is required, it MUST be generated and checked
in accordance with the conventions specified in [ESP].

3.3. Authentication Data

AES CCM provides an encrypted ICV. The ICV provided by CCM is
carried in the Authentication Data fields without further encryption.
Implementations MUST support ICV sizes of 8 octets and 16 octets.
Implementations MAY also support ICV 12 octets.

4. Nonce Format

Each packet conveys the IV that is necessary to construct the
sequence of counter blocks used by counter mode to generate the key
stream. The AES counter block is 16 octets. One octet is used for
the CCM Flags, and 4 octets are used for the block counter, as
specified by the CCM L parameter. The remaining octets are the
nonce. These octets occupy the second through the twelfth octets in
the counter block. Figure 2 shows the format of the nonce.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                    |                    Salt                   |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                   Initialization Vector                     |
 |                                                             |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
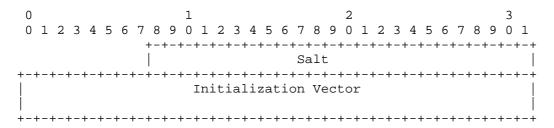
Figure 2. Nonce Format

The components of the nonce are as follows:

Salt The salt field is 24 bits. As the name implies, it contains
    an unpredictable value. It MUST be assigned at the beginning
    of the security association. The salt value need not be
    secret, but it MUST NOT be predictable prior to the beginning
    of the security association.

Initialization Vector The IV field is 64 bits. As described in
    Section 3.1, the IV MUST be chosen by the encryptor in a manner
    that ensures that the same IV value is used only once for a
    given key.

This construction permits each packet to consist of up to:

         2^32 blocks = 4,294,967,296 blocks
                      = 68,719,476,736 octets

This construction provides more key stream for each packet than is
needed to handle any IPv6 Jumbogram [JUMBO].

5. AAD Construction

The data integrity and data origin authentication for the Security
Parameters Index (SPI) and (Extended) Sequence Number fields is
provided without encrypting them. Two formats are defined: one for
32-bit sequence numbers and one for 64-bit extended sequence numbers.
The format with 32-bit sequence numbers is shown in Figure 3, and the
format with 64-bit extended sequence numbers is shown in Figure 4.

Sequence Numbers are conveyed canonical network byte order. Extended
Sequence Numbers are conveyed canonical network byte order, placing
the high-order 32 bits first and the low-order 32 bits second.
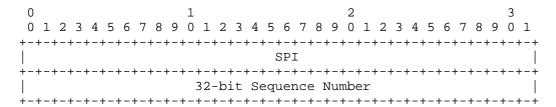Canonical network byte order is fully described in RFC 791, Appendix
B.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             SPI                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    32-bit Sequence Number                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

           Figure 3. AAD Format with 32-bit Sequence Number

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             SPI                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               64-bit Extended Sequence Number                 |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
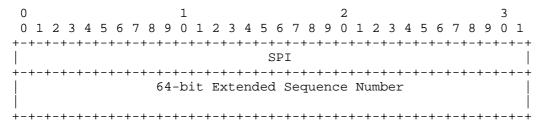
         Figure 4. AAD Format with 64-bit Extended Sequence Number

6. Packet Expansion

   The initialization vector (IV) and the integrity check value (ICV)
   are the only sources of packet expansion. The IV always adds 8
   octets to the front of the payload. The ICV is added at the end of
   the payload, and the CCM parameter M determines the size of the ICV.
   Implementations MUST support M values of 8 octets and 16 octets, and
   implementations MAY also support an M value of 12 octets.

7. IKE Conventions

   This section describes the conventions used to generate keying
   material and salt values for use with AES CCM using the Internet Key
   Exchange (IKE) [IKE] protocol. The identifiers and attributes needed
   to negotiate a security association that uses AES CCM are also
   defined.

7.1. Keying Material and Salt Values

   As previously described, implementations MUST use fresh keys with AES
   CCM. IKE can be used to establish fresh keys. This section
   describes the conventions for obtaining the unpredictable salt value
   for use in the nonce from IKE. Note that this convention provides a
   salt value that is secret as well as unpredictable.

   IKE makes use of a pseudo-random function (PRF) to derive keying
   material. The PRF is used iteratively to derive keying material of
   arbitrary size, called KEYMAT. Keying material is extracted from the
   output string without regard to boundaries.

   The size of KEYMAT MUST be three octets longer than is needed for the
   associated AES key. The keying material is used as follows:

      AES CCM with a 128-bit key
         The KEYMAT requested for each AES CCM key is 19 octets. The
         first 16 octets are the 128-bit AES key, and the remaining
         three octets are used as the salt value in the counter block.

      AES CCM with a 192-bit key
         The KEYMAT requested for each AES CCM key is 27 octets. The
         first 24 octets are the 192-bit AES key, and the remaining
         three octets are used as the salt value in the counter block.

      AES CCM with a 256-bit key
         The KEYMAT requested for each AES CCM key is 35 octets. The
         first 32 octets are the 256-bit AES key, and the remaining
         three octets are used as the salt value in the counter block.

7.2. Phase 1 Identifier

   This document does not specify the conventions for using AES CCM for
   IKE Phase 1 negotiations. For AES CCM to be used in this manner, a
   separate specification is needed, and an Encryption Algorithm
   Identifier needs to be assigned.

7.3. Phase 2 Identifier

   For IKE Phase 2 negotiations, IANA has assigned three ESP Transform
   Identifiers for AES CCM with an explicit IV:

      14 for AES CCM with an 8-octet ICV;
      15 for AES CCM with a 12-octet ICV; and
      16 for AES CCM with a 16-octet ICV.

7.4. Key Length Attribute

   Because the AES supports three key lengths, the Key Length attribute
   MUST be specified in the IKE Phase 2 exchange [DOI]. The Key Length
   attribute MUST have a value of 128, 192, or 256.

8. Test Vectors

   Section 8 of [CCM] provides test vectors that will assist
   implementers with AES CCM mode.

9. Security Considerations

   AES CCM employs counter (CTR) mode for confidentiality. If a counter
   value is ever used for more that one packet with the same key, then
   the same key stream will be used to encrypt both packets, and the
   confidentiality guarantees are voided.

   What happens if the encryptor XORs the same key stream with two
   different packet plaintexts? Suppose two packets are defined by two
   plaintext byte sequences P1, P2, P3 and Q1, Q2, Q3, then both are
   encrypted with key stream K1, K2, K3. The two corresponding
   ciphertexts are:

      (P1 XOR K1), (P2 XOR K2), (P3 XOR K3)

      (Q1 XOR K1), (Q2 XOR K2), (Q3 XOR K3)

   If both of these two ciphertext streams are exposed to an attacker,
   then a catastrophic failure of confidentiality results, because:

```
(P1 XOR K1) XOR (Q1 XOR K1) = P1 XOR Q1
(P2 XOR K2) XOR (Q2 XOR K2) = P2 XOR Q2
(P3 XOR K3) XOR (Q3 XOR K3) = P3 XOR Q3
```

Once the attacker obtains the two plaintexts XORed together, it is
relatively straightforward to separate them. Thus, using any stream
cipher, including AES CTR, to encrypt two plaintexts under the same
key stream leaks the plaintext.

Therefore, AES CCM should not be used with statically configured
keys. Extraordinary measures would be needed to prevent the reuse of
a counter block value with the static key across power cycles. To be
safe, implementations MUST use fresh keys with AES CCM. The IKE
[IKE] protocol can be used to establish fresh keys.

When IKE is used to establish fresh keys between two peer entities,
separate keys are established for the two traffic flows. If a
different mechanism is used to establish fresh keys, one that

establishes only a single key to encrypt packets, then there is a
high probability that the peers will select the same IV values for
some packets. Thus, to avoid counter block collisions, ESP
implementations that permit use of the same key for encrypting and
decrypting packets with the same peer MUST ensure that the two peers
assign different salt values to the security association (SA).

Regardless of the mode used, AES with a 128-bit key is vulnerable to
the birthday attack after 2^{64} blocks are encrypted with a single
key. Since ESP with Extended Sequence Numbers allows for up to 2^{64}
packets in a single SA, there is real potential for more than 2^{64}
blocks to be encrypted with one key. Implementations SHOULD generate
a fresh key before 2^{64} blocks are encrypted with the same key, or
implementations SHOULD make use of the longer AES key sizes. Note
that ESP with 32-bit Sequence Numbers will not exceed 2^{64} blocks
even if all of the packets are maximum-length Jumbograms.

10. Design Rationale

In the development of this specification, the use of the ESP sequence
number field instead of an explicit IV field was considered. This
section documents the rationale for the selection of an explicit IV.
This selection is not a cryptographic security issue, as either
approach will prevent counter block collisions.

The use of the explicit IV does not dictate the manner that the
encryptor uses to assign the per-packet value in the counter block.
This is desirable for several reasons.

   1. Only the encryptor can ensure that the value is not used for
   more than one packet, so there is no advantage to selecting a
   mechanism that allows the decryptor to determine whether counter
   block values collide. Damage from the collision is done, whether
   the decryptor detects it or not.

   2. The use of explicit IVs allows adders, LFSRs, and any other
   technique that meets the time budget of the encryptor, so long as
   the technique results in a unique value for each packet. Adders
   are simple and straightforward to implement, but due to carries,
   they do not execute in constant time. LFSRs offer an alternative
   that executes in constant time.

   3. Complexity is in control of the implementer. Furthermore, the
   decision made by the implementer of the encryptor does not make
   the decryptor more (or less) complex.

   4. The assignment of the per-packet counter block value needs to
   be inside the assurance boundary. Some implementations assign the
   sequence number inside the assurance boundary, but others do not.
   A sequence number collision does not have the dire consequences,
   but, as described in Section 6, a collision in counter block
   values has disastrous consequences.

   5. Using the sequence number as the IV is possible in those
   architectures where the sequence number assignment is performed
   within the assurance boundary. In this situation, the sequence
   number and the IV field will contain the same value.

   6. By decoupling the IV and the sequence number, architectures
   where the sequence number assignment is performed outside the
   assurance boundary are accommodated.

The use of an explicit IV field directly follows from the decoupling
of the sequence number and the per-packet counter block value. The
additional overhead (64 bits for the IV field) is acceptable. This
overhead is significantly less overhead associated with Cipher Block
Chaining (CBC) mode. As normally employed, CBC requires a full block
for the IV and, on average, half of a block for padding. AES CCM
confidentiality processing with an explicit IV has about one-third of
the overhead as AES CBC, and the overhead is constant for each
packet.

11. IANA Considerations

   IANA has assigned three ESP transform numbers for use with AES CCM
   with an explicit IV:

      14 for AES CCM with an 8-octet ICV;
      15 for AES CCM with a 12-octet ICV; and
      16 for AES CCM with a 16-octet ICV.

12. Acknowledgements

   Doug Whiting and Niels Ferguson worked with me to develop CCM mode.
   We developed CCM mode as part of the IEEE 802.11i security effort.
   One of the most attractive aspects of CCM mode is that it is
   unencumbered by patents. I acknowledge the companies that supported
   the development of an unencumbered authenticated encryption mode (in
   alphabetical order):

      Hifn
      Intersil
      MacFergus
      RSA Security

   Also, I thank Tero Kivinen for his comprehensive review of this
   document.

13. References

   This section provides normative and informative references.

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