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Using GOST Ciphers in the Encapsulating Security Payload (ESP) and
         Internet Key Exchange Version 2 (IKEv2) Protocols

Abstract

   This document defines a set of encryption transforms for use in the
   Encapsulating Security Payload (ESP) and in the Internet Key Exchange
   version 2 (IKEv2) protocols, which are parts of the IP Security
   (IPsec) protocol suite. The transforms are based on the GOST R
   34.12-2015 block ciphers (which are named "Magma" and "Kuznyechik")
   in Multilinear Galois Mode (MGM) and the external rekeying approach.

   This specification was developed to facilitate implementations that
   wish to support the GOST algorithms. This document does not imply
   IETF endorsement of the cryptographic algorithms used in this
   document.

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1. Introduction

   The IP Security (IPsec) protocol suite consists of several protocols,
   of which the Encapsulating Security Payload (ESP) [RFC4303] and the
   Internet Key Exchange version 2 (IKEv2) [RFC7296] are most widely
   used. This document defines four transforms for ESP and IKEv2 based
   on Russian cryptographic standard algorithms (often referred to as
   "GOST" algorithms). These definitions are based on the
   recommendations [GOST-ESP] established by the Federal Agency on
   Technical Regulating and Metrology (Rosstandart), which describe how
   Russian cryptographic standard algorithms are used in ESP and IKEv2.
   The transforms defined in this document are based on two block
   ciphers from Russian cryptographic standard algorithms --
   "Kuznyechik" [GOST3412-2015] [RFC7801] and "Magma" [GOST3412-2015]
   [RFC8891] in Multilinear Galois Mode (MGM) [GOST-MGM] [RFC9058].
   These transforms provide Authenticated Encryption with Associated
   Data (AEAD). An external rekeying mechanism, described in [RFC8645],
   is also used in these transforms to limit the load on session keys.

   Because the GOST specification includes the definition of both
   128-bit ("Kuznyechik") and 64-bit ("Magma") block ciphers, both are
   included in this document. Implementers should make themselves aware
   of the relative security and other cost-benefit implications of the
   two ciphers. See Section 5 for more details.

   This specification was developed to facilitate implementations that
   wish to support the GOST algorithms. This document does not imply
   IETF endorsement of the cryptographic algorithms used in this
   document.

2. Requirements Language

   The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
   "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and
   "OPTIONAL" in this document are to be interpreted as described in
   BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all
   capitals, as shown here.

3. Overview

   Russian cryptographic standard algorithms, often referred to as
   "GOST" algorithms, constitute a set of cryptographic algorithms of
   different types -- ciphers, hash functions, digital signatures, etc.
   In particular, Russian cryptographic standard [GOST3412-2015] defines
   two block ciphers -- "Kuznyechik" (also defined in [RFC7801]) and
   "Magma" (also defined in [RFC8891]). Both ciphers use a 256-bit key.
   "Kuznyechik" has a block size of 128 bits, while "Magma" has a 64-bit
   block.

   Multilinear Galois Mode (MGM) is an AEAD mode defined in [GOST-MGM]
   and [RFC9058]. It is claimed to provide defense against some attacks
   on well-known AEAD modes, like Galois/Counter Mode (GCM).

   [RFC8645] defines mechanisms that can be used to limit the number of
   times any particular session key is used. One of these mechanisms,
   called external rekeying with tree-based construction (defined in
   Section 5.2.3 of [RFC8645]), is used in the defined transforms. For
   the purpose of deriving subordinate keys, the Key Derivation Function

(KDF) KDF_GOSTR3411_2012_256, defined in Section 4.5 of [RFC7836], is
used. This KDF is based on a Hashed Message Authentication Code
(HMAC) construction [RFC2104] with a Russian GOST hash function
defined in Russian cryptographic standard [GOST3411-2012] (also
defined in [RFC6986]).

4. Description of Transforms

   This document defines four transforms of Type 1 (Encryption
   Algorithm) for use in ESP and IKEv2. All of them use MGM as the mode
   of operation with tree-based external rekeying. The transforms
   differ in underlying ciphers and in cryptographic services they
   provide.

   * ENCR_KUZNYECHIK_MGM_KTREE (Transform ID 32) is an AEAD transform
      based on the "Kuznyechik" algorithm; it provides confidentiality
      and message authentication and thus can be used in both ESP and
      IKEv2.

   * ENCR_MAGMA_MGM_KTREE (Transform ID 33) is an AEAD transform based
      on the "Magma" algorithm; it provides confidentiality and message
      authentication and thus can be used in both ESP and IKEv2.

   * ENCR_KUZNYECHIK_MGM_MAC_KTREE (Transform ID 34) is a MAC-only
      transform based on the "Kuznyechik" algorithm; it provides no
      confidentiality and thus can only be used in ESP, but not in
      IKEv2.

   * ENCR_MAGMA_MGM_MAC_KTREE (Transform ID 35) is a MAC-only transform
      based on the "Magma" algorithm; it provides no confidentiality and
      thus can only be used in ESP, but not in IKEv2.

   Note that transforms ENCR_KUZNYECHIK_MGM_MAC_KTREE and
   ENCR_MAGMA_MGM_MAC_KTREE don't provide any confidentiality, but they
   are defined as Type 1 (Encryption Algorithm) transforms because of
   the need to include an Initialization Vector (IV), which is
   impossible for Type 3 (Integrity Algorithm) transforms.

4.1. Tree-Based External Rekeying

   All four transforms use the same tree-based external rekeying
   mechanism. The idea is that the key that is provided for the
   transform is not directly used to protect messages. Instead, a tree
   of keys is derived using this key as a root. This tree may have
   several levels. The leaf keys are used for message protection, while
   intermediate-node keys are used to derive lower-level keys, including
   leaf keys. See Section 5.2.3 of [RFC8645] for more details. This
   construction allows us to protect a large amount of data, at the same
   time providing a bound on a number of times any particular key in the
   tree is used, thus defending against some side-channel attacks and
   also increasing the key lifetime limitations based on combinatorial
   properties.

   The transforms defined in this document use a three-level tree. The
   leaf key that protects a message is computed as follows:

        K_msg = KDF (KDF (KDF (K, l1, 0x00 | i1), l2, i2), l3, i3)

   where:

   KDF (k, l, s)   Key Derivation Function KDF_GOSTR3411_2012_256
                    (defined in Section 4.5 of [RFC7836]), which accepts
                    three input parameters -- a key (k), a label (l), and
                    a seed (s) -- and provides a new key as output

   K   the root key for the tree (see Section 4.4)

   l1, l2, l3   labels defined as 6-octet ASCII strings without null
                    termination:

                    l1 = "level1"

```
                  l2  =  "level2"

                  l3  =  "level3"

   i1, i2, i3        parameters that determine which keys out of the tree
                     are used on each level.  Together, they determine a
                     leaf key that is used for message protection; the
                     length of i1 is one octet, and i2 and i3 are two-
                     octet integers in network byte order

   |                 indicates concatenation
```

This construction allows us to generate up to 2^8 keys on level 1 and up to 2^{16} keys on levels 2 and 3. So, the total number of possible leaf keys generated from a single Security Association (SA) key is 2^{40}.

This specification doesn't impose any requirements on how frequently external rekeying takes place. It is expected that the sending application will follow its own policy dictating how many times the keys on each level must be used.

4.2. Initialization Vector Format

Each message protected by the defined transforms MUST contain an IV. The IV has a size of 64 bits and consists of four fields. The fields i1, i2, and i3 are parameters that determine the particular leaf key this message was protected with (see Section 4.1). The fourth field is a counter, representing the message number for this key.

```
                     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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      i1       |              i2               |      i3       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  i3 (cont)    |                   pnum                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
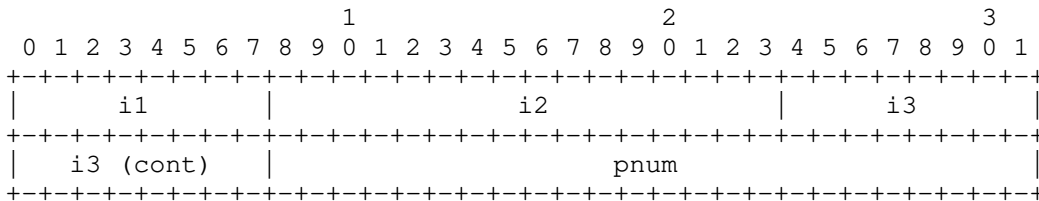
                        Figure 1: IV Format

where:

   i1 (1 octet), i2 (2 octets), i3 (2 octets): parameters that
      determine the particular key used to protect this message; 2-octet
      parameters are integers in network byte order

   pnum (3 octets): message counter in network byte order for the leaf
      key protecting this message; up to 2^{24} messages may be protected
      using a single leaf key

For any given SA, the IV MUST NOT be used more than once, but there is no requirement that IV be unpredictable.

4.3. Nonce Format for MGM

MGM requires a per-message nonce (called the Initial Counter Nonce, or ICN in [RFC9058]) that MUST be unique in the context of any leaf key. The size of the ICN is $n-1$ bits, where n is the block size of the underlying cipher. The two ciphers used in the transforms defined in this document have different block sizes, so two different formats for the ICN are defined.

MGM specification requires that the nonce be $n-1$ bits in size, where n is the block size of the underlying cipher. This document defines MGM nonces having n bits (the block size of the underlying cipher) in size. Since n is always a multiple of 8 bits, this makes MGM nonces having a whole number of octets. When used inside MGM, the most significant bit of the first octet of the nonce (represented as an octet string) is dropped, making the effective size of the nonce equal to $n-1$ bits. Note that the dropped bit is a part of the "zero"

field (see Figures 2 and 3), which is always set to 0, so no
information is lost when it is dropped.

4.3.1. MGM Nonce Format for Transforms Based on the "Kuznyechik" Cipher

   For transforms based on the "Kuznyechik" cipher
   (ENCR_KUZNYECHIK_MGM_KTREE and ENCR_KUZNYECHIK_MGM_MAC_KTREE), the
   ICN consists of a "zero" octet; a 24-bit message counter; and a
   96-bit secret salt, which is fixed for the SA and is not transmitted.

```
                     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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     zero      |                    pnum                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
|                                                               |
|                            salt                               |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
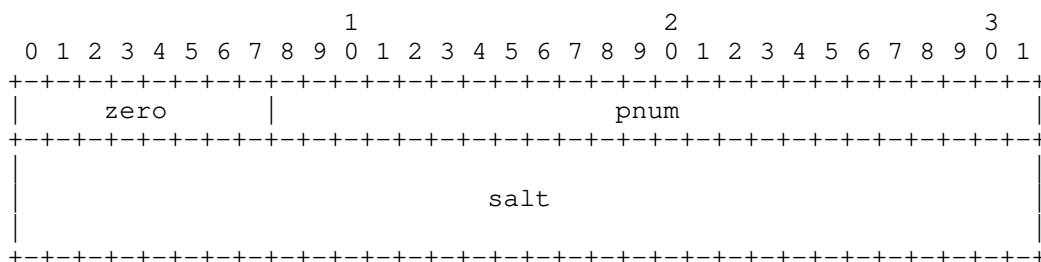
        Figure 2: Nonce Format for Transforms Based on the "Kuznyechik"
                                    Cipher

   where:

   zero (1 octet): set to 0

   pnum (3 octets): the counter for the messages protected by the given
      leaf key; this field MUST be equal to the pnum field in the IV

   salt (12 octets): secret salt. The salt is a string of bits that
      are formed when the SA is created (see Section 4.4 for details).
      The salt does not change during the SA's lifetime and is not
      transmitted on the wire. Every SA will have its own salt.

4.3.2. MGM Nonce Format for Transforms Based on the "Magma" Cipher

   For transforms based on the "Magma" cipher (ENCR_MAGMA_MGM_KTREE and
   ENCR_MAGMA_MGM_MAC_KTREE), the ICN consists of a "zero" octet; a
   24-bit message counter; and a 32-bit secret salt, which is fixed for
   the SA and is not transmitted.

```
                     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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     zero      |                    pnum                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            salt                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
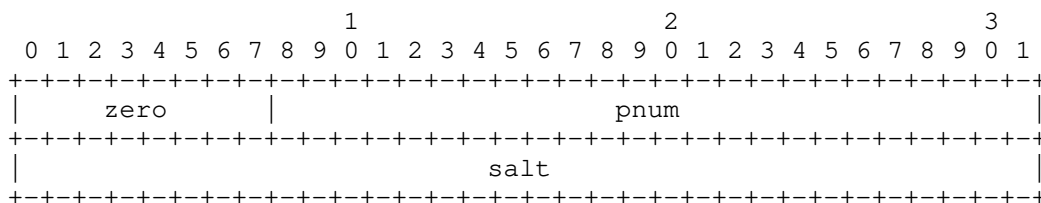
        Figure 3: Nonce Format for Transforms Based on the "Magma" Cipher

   where:

   zero (1 octet): set to 0

   pnum (3 octets): the counter for the messages protected by the given
      leaf key; this field MUST be equal to the pnum field in the IV

   salt (4 octets): secret salt. The salt is a string of bits that are
      formed when the SA is created (see Section 4.4 for details). The
      salt does not change during the SA's lifetime and is not
      transmitted on the wire. Every SA will have its own salt.

4.4. Keying Material

   We'll call a string of bits that is used to initialize the transforms
   defined in this specification a "transform key". The transform key
   is a composite entity consisting of the root key for the tree and the
   secret salt.

The transform key for the ENCR_KUZNYECHIK_MGM_KTREE and
ENCR_KUZNYECHIK_MGM_MAC_KTREE transforms consists of 352 bits (44
octets), of which the first 256 bits is a root key for the tree
(denoted as K in Section 4.1) and the remaining 96 bits is a secret
salt (see Section 4.3.1).

The transform key for the ENCR_MAGMA_MGM_KTREE and
ENCR_MAGMA_MGM_MAC_KTREE transforms consists of 288 bits (36 octets),
of which the first 256 bits is a root key for the tree (denoted as K
in Section 4.1) and the remaining 32 bits is a secret salt (see
Section 4.3.2).

In the case of ESP, the transform keys are extracted from the KEYMAT
as defined in Section 2.17 of [RFC7296]. In the case of IKEv2, the
transform keys are either SK_ei or SK_er, which are generated as
defined in Section 2.14 of [RFC7296]. Note that since these
transforms provide authenticated encryption, no additional keys are
needed for authentication. This means that, in the case of IKEv2,
the keys SK_ai/SK_ar are not used and MUST be treated as having zero
length.

4.5. Integrity Check Value

The length of the authentication tag that MGM can compute is in the
range from 32 bits to the block size of the underlying cipher.
Section 4 of [RFC9058] states that the authentication tag length MUST
be fixed for a particular protocol. For transforms based on the
"Kuznyechik" cipher (ENCR_KUZNYECHIK_MGM_KTREE and
ENCR_KUZNYECHIK_MGM_MAC_KTREE), the resulting Integrity Check Value
(ICV) length is set to 96 bits. For transforms based on the "Magma"
cipher (ENCR_MAGMA_MGM_KTREE and ENCR_MAGMA_MGM_MAC_KTREE), the full
ICV length is set to the block size (64 bits).

4.6. Plaintext Padding

The transforms defined in this document don't require any plaintext
padding, as specified in [RFC9058]. This means that only those
padding requirements that are imposed by the protocol are applied (4
bytes for ESP, no padding for IKEv2).

4.7. AAD Construction

4.7.1. ESP AAD

Additional Authenticated Data (AAD) in ESP is constructed
differently, depending on the transform being used and whether the
Extended Sequence Number (ESN) is in use or not. The
ENCR_KUZNYECHIK_MGM_KTREE and ENCR_MAGMA_MGM_KTREE transforms provide
confidentiality, so the content of the ESP body is encrypted and the
AAD consists of the ESP Security Parameter Index (SPI) and (E)SN.
The AAD is constructed similarly to the AAD in [RFC4106].

On the other hand, the ENCR_KUZNYECHIK_MGM_MAC_KTREE and
ENCR_MAGMA_MGM_MAC_KTREE transforms don't provide confidentiality;
they provide only message authentication. For this purpose, the IV
and the part of the ESP packet that is normally encrypted are
included in the AAD. For these transforms, the encryption capability
provided by MGM is not used. The AAD is constructed similarly to the
AAD in [RFC4543].

```
                      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                     |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
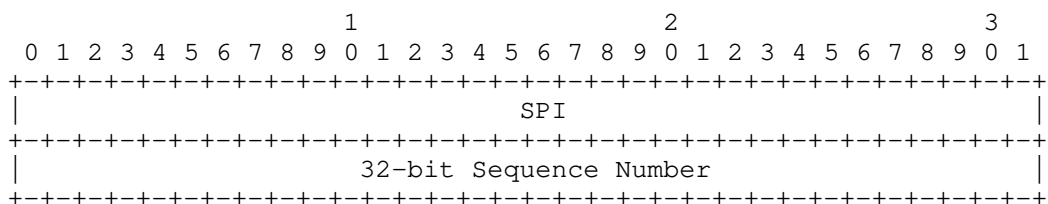
Figure 4: AAD for AEAD Transforms with 32-Bit SN

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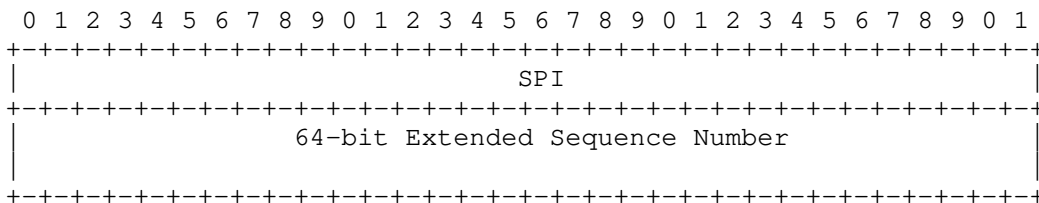
```
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                              SPI                              |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                 64-bit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

             Figure 5: AAD for AEAD Transforms with 64-Bit ESN

                       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                   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                              IV                               |
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   ~                     Payload Data (variable)                   ~
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                     Padding (0-255 bytes)                     |
   +                           +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                           |  Pad Length   |  Next Header      |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

         Figure 6: AAD for Authentication-Only Transforms with 32-Bit SN

                       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               |
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                              IV                               |
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   ~                     Payload Data (variable)                   ~
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                     Padding (0-255 bytes)                     |
   +                           +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                           |  Pad Length   |  Next Header      |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

         Figure 7: AAD for Authentication-Only Transforms with 64-Bit ESN
```
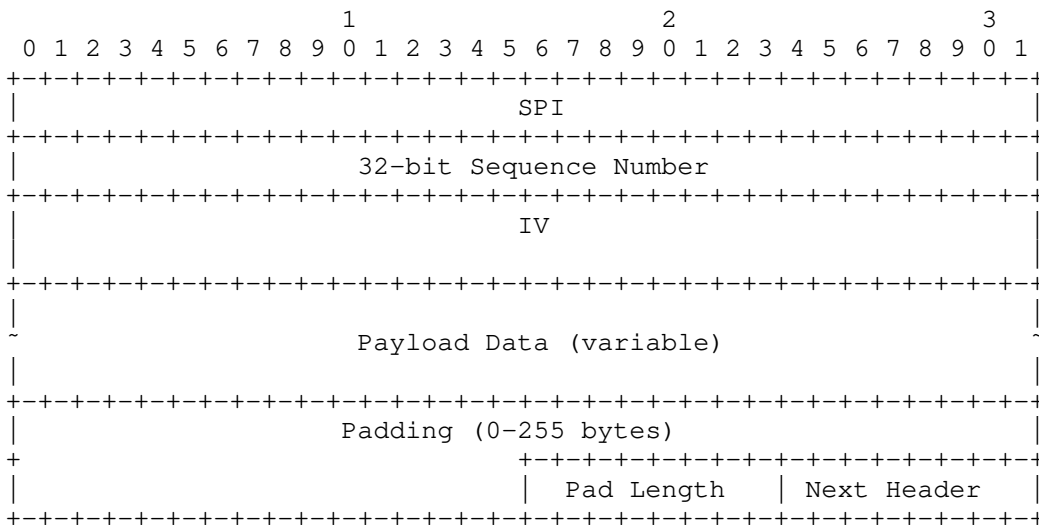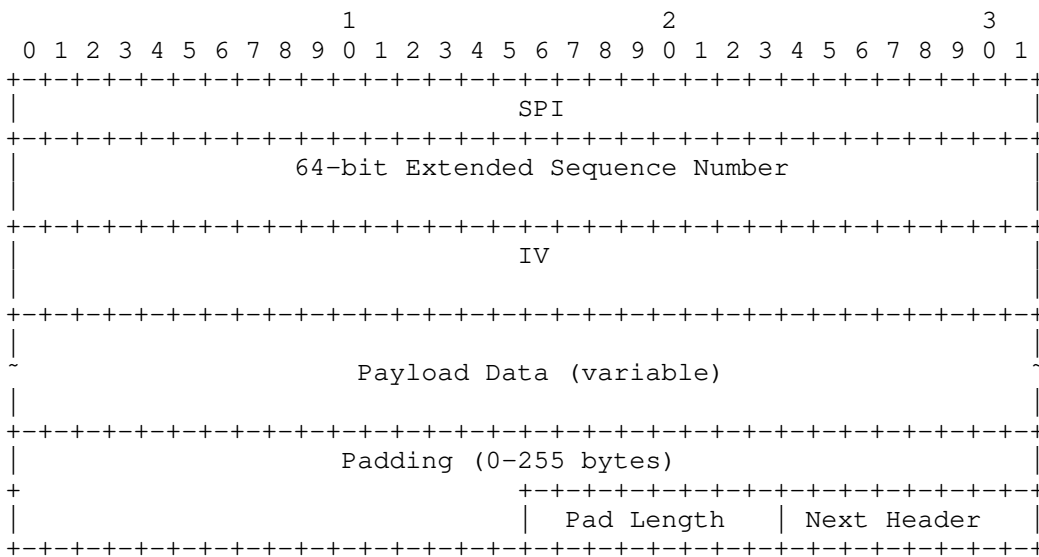
4.7.2. IKEv2 AAD

   For IKEv2, the AAD consists of the IKEv2 Header, any unencrypted
   payloads following it (if present), and either the Encrypted payload
   header (Section 3.14 of [RFC7296]) or the Encrypted Fragment payload
   (Section 2.5 of [RFC7383]), depending on whether IKE fragmentation is
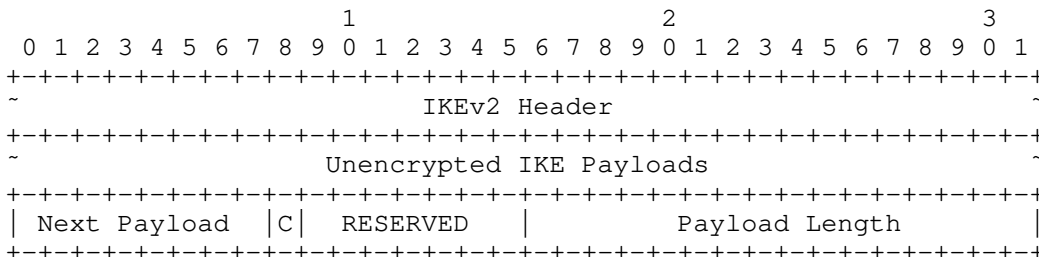   used. The AAD is constructed similarly to the AAD in [RFC5282].

```
                       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
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   ~                          IKEv2 Header                         ~
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   ~                     Unencrypted IKE Payloads                  ~
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   | Next Payload  |C|  RESERVED   |         Payload Length        |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 8: AAD for IKEv2 in the Case of the Encrypted Payload

```
                      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
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 ~                          IKEv2 Header                         ~
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 ~                    Unencrypted IKE Payloads                   ~
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 | Next Payload  |C|  RESERVED   |         Payload Length        |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |        Fragment Number        |        Total Fragments        |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
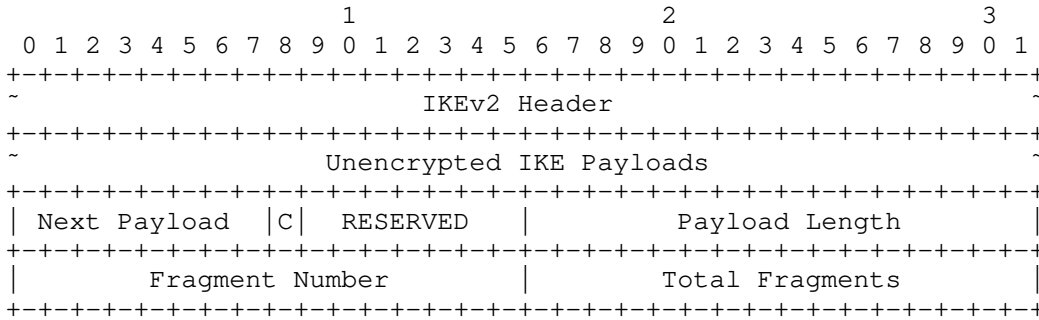
Figure 9: AAD for IKEv2 in the Case of the Encrypted Fragment Payload

4.8. Using Transforms

When the SA is established, the i1, i2, and i3 parameters are set to
0 by the sender and a leaf key is calculated. The pnum parameter
starts from 0 and is incremented with each message protected by the
same leaf key. When the sender decides that the leaf should be
changed, it increments the i3 parameter and generates a new leaf key.
The pnum parameter for the new leaf key is reset to 0, and the
process continues. If the sender decides that a third-level key
corresponding to i3 is used enough times, it increments i2, resets i3
to 0, and calculates a new leaf key. The pnum is reset to 0 (as with
every new leaf key), and the process continues. A similar procedure
is used when a second-level key needs to be changed.

A combination of i1, i2, i3, and pnum MUST NOT repeat for any
particular SA. This means that the wrapping of these counters is not
allowed: when i2, i3, or pnum reaches its respective maximum value, a
procedure for changing a leaf key, described above, is executed, and
if all four parameters reach their maximum values, the IPsec SA
becomes unusable.

There may be other reasons to recalculate leaf keys besides reaching
maximum values for the counters. For example, as described in
Section 5, it is RECOMMENDED that the sender count the number of
octets protected by a particular leaf key and generate a new key when
some threshold is reached, and at the latest when reaching the octet
limits stated in Section 5 for each of the ciphers.

The receiver always uses i1, i2, and i3 from the received message.
If they differ from the values in previously received packets, a new
leaf key is calculated. The pnum parameter is always used from the
received packet. To improve performance, implementations may cache
recently used leaf keys. When a new leaf key is calculated (based on
the values from the received message), the old key may be kept for
some time to improve performance in the case of possible packet
reordering (when packets protected by the old leaf key are delayed
and arrive later).

5. Security Considerations

The most important security consideration for MGM is that the nonce
MUST NOT repeat for a given key. For this reason, the transforms
defined in this document MUST NOT be used with manual keying.

Excessive use of the same key can give an attacker advantages in
breaking security properties of the transforms defined in this
document. For this reason, the amount of data that any particular
key is used to protect should be limited. This is especially
important for algorithms with a 64-bit block size (like "Magma"),
which currently are generally considered insecure after protecting a
relatively small amount of data. For example, Section 3.4 of
[SP800-67] limits the number of blocks that are allowed to be
encrypted with the Triple DES cipher to 2^{20} (8 MB of data). This
document defines a rekeying mechanism that allows the mitigation of
weak security of a 64-bit block cipher by frequently changing the

encryption key.

For transforms defined in this document, [GOST-ESP] recommends
limiting the number of octets protected with a single K_msg key by
the following values:

* 2^{41} octets for transforms based on the "Kuznyechik" cipher
    (ENCR_KUZNYECHIK_MGM_KTREE and ENCR_KUZNYECHIK_MGM_MAC_KTREE)

* 2^{28} octets for transforms based on the "Magma" cipher
    (ENCR_MAGMA_MGM_KTREE and ENCR_MAGMA_MGM_MAC_KTREE)

These values are based on combinatorial properties and may be further
restricted if side-channel attacks are taken into consideration.
Note that the limit for transforms based on the "Kuznyechik" cipher
is unreachable because, due to the construction of the transforms,
the number of protected messages is limited to 2^{24} and each message
(either IKEv2 messages or ESP datagrams) is limited to 2^{16} octets in
size, giving 2^{40} octets as the maximum amount of data that can be
protected with a single K_msg.

Section 4 of [RFC9058] discusses the possibility of truncating
authentication tags in MGM as a trade-off between message expansion
and the probability of forgery. This specification truncates an
authentication tag length for transforms based on the "Kuznyechik"
cipher to 96 bits. This decreases message expansion while still
providing a very low probability of forgery: 2^{-96}.

An attacker can send a lot of packets with arbitrarily chosen i1, i2,
and i3 parameters. This will 1) force a recipient to recalculate the
leaf key for every received packet if i1, i2, and i3 are different
from these values in previously received packets, thus consuming CPU
resources and 2) force a recipient to make verification attempts
(that would fail) on a large amount of data, thus allowing the
attacker a deeper analysis of the underlying cryptographic primitive
(see [AEAD-USAGE-LIMITS]). Implementations MAY initiate rekeying if
they deem that they receive too many packets with an invalid ICV.

Security properties of MGM are discussed in [MGM-SECURITY].

6. IANA Considerations

   IANA maintains a registry called "Internet Key Exchange Version 2
   (IKEv2) Parameters" with a subregistry called "Transform Type
   Values". IANA has added the following four Transform IDs to the
   "Transform Type 1 - Encryption Algorithm Transform IDs" subregistry.

Number	Name	ESP Reference	IKEv2 Reference
32	ENCR_KUZNYECHIK_MGM_KTREE	RFC 9227	RFC 9227
33	ENCR_MAGMA_MGM_KTREE	RFC 9227	RFC 9227
34	ENCR_KUZNYECHIK_MGM_MAC_KTREE	RFC 9227	Not allowed
35	ENCR_MAGMA_MGM_MAC_KTREE	RFC 9227	Not allowed

Table 1: Transform IDs

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Appendix A. Test Vectors

   In the following test vectors, binary data is represented in
   hexadecimal format. The numbers in square brackets indicate the size
   of the corresponding data in decimal format.

   1. ENCR_KUZNYECHIK_MGM_KTREE (Example 1):

       transform key [44]:
           b6 18 0c 14 5c 51 2d bd 69 d9 ce a9 2c ac 1b 5c
           e1 bc fa 73 79 2d 61 af 0b 44 0d 84 b5 22 cc 38
           7b 67 e6 f2 44 f9 7f 06 78 95 2e 45
       K [32]:
           b6 18 0c 14 5c 51 2d bd 69 d9 ce a9 2c ac 1b 5c
           e1 bc fa 73 79 2d 61 af 0b 44 0d 84 b5 22 cc 38
       salt [12]:
           7b 67 e6 f2 44 f9 7f 06 78 95 2e 45
       i1 = 00, i2 = 0000, i3 = 0000, pnum = 000000
       K_msg [32]:
           2f f1 c9 0e de 78 6e 06 1e 17 b3 74 d7 82 af 7b
           d8 80 bd 52 7c 66 a2 ba dc 3e 56 9a ab 27 1d a4
       nonce [16]:
           00 00 00 00 7b 67 e6 f2 44 f9 7f 06 78 95 2e 45
       IV [8]:
           00 00 00 00 00 00 00 00
       AAD [8]:
           51 46 53 6b 00 00 00 01
       plaintext [64]:
           45 00 00 3c 23 35 00 00 7f 01 ee cc 0a 6f 0a c5

```
        0a 6f 0a 1d 08 00 f3 5b 02 00 58 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
    ciphertext [64]:
        18 9d 12 88 b7 18 f9 ea be 55 4b 23 9b ee 65 96
        c6 d4 ea fd 31 64 96 ef 90 1c ac 31 60 05 aa 07
        62 97 b2 24 bf 6d 2b e3 5f d6 f6 7e 7b 9d eb 31
        85 ff e9 17 9c a9 bf 0b db af c2 3e ae 4d a5 6f
    ESP ICV [12]:
        50 b0 70 a1 5a 2b d9 73 86 89 f8 ed
    ESP packet [112]:
        45 00 00 70 00 4d 00 00 ff 32 91 4f 0a 6f 0a c5
        0a 6f 0a 1d 51 46 53 6b 00 00 00 01 00 00 00 00
        00 00 00 00 18 9d 12 88 b7 18 f9 ea be 55 4b 23
        9b ee 65 96 c6 d4 ea fd 31 64 96 ef 90 1c ac 31
        60 05 aa 07 62 97 b2 24 bf 6d 2b e3 5f d6 f6 7e
        7b 9d eb 31 85 ff e9 17 9c a9 bf 0b db af c2 3e
        ae 4d a5 6f 50 b0 70 a1 5a 2b d9 73 86 89 f8 ed
```

2. ENCR_KUZNYECHIK_MGM_KTREE (Example 2):

```
    transform key [44]:
        b6 18 0c 14 5c 51 2d bd 69 d9 ce a9 2c ac 1b 5c
        e1 bc fa 73 79 2d 61 af 0b 44 0d 84 b5 22 cc 38
        7b 67 e6 f2 44 f9 7f 06 78 95 2e 45
    K [32]:
        b6 18 0c 14 5c 51 2d bd 69 d9 ce a9 2c ac 1b 5c
        e1 bc fa 73 79 2d 61 af 0b 44 0d 84 b5 22 cc 38
    salt [12]:
        7b 67 e6 f2 44 f9 7f 06 78 95 2e 45
    i1 = 00, i2 = 0001, i3 = 0001, pnum = 000000
    K_msg [32]:
        9a ba c6 57 78 18 0e 6f 2a f6 1f b8 d5 71 62 36
        66 c2 f5 13 0d 54 e2 11 6c 7d 53 0e 6e 7d 48 bc
    nonce [16]:
        00 00 00 00 7b 67 e6 f2 44 f9 7f 06 78 95 2e 45
    IV [8]:
        00 00 01 00 01 00 00 00
    AAD [8]:
        51 46 53 6b 00 00 00 10
    plaintext [64]:
        45 00 00 3c 23 48 00 00 7f 01 ee b9 0a 6f 0a c5
        0a 6f 0a 1d 08 00 e4 5b 02 00 67 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
    ciphertext [64]:
        78 0a 2c 62 62 32 15 7b fe 01 76 32 f3 2d b4 d0
        a4 fa 61 2f 66 c2 bf 79 d5 e2 14 9b ac 1d fc 4b
        15 4b 69 03 4d c2 1d ef 20 90 6d 59 62 81 12 7c
        ff 72 56 ab f0 0b a1 22 bb 5e 6c 71 a4 d4 9a 4d
    ESP ICV [12]:
        c2 2f 87 40 83 8e 3d fa ce 91 cc b8
    ESP packet [112]:
        45 00 00 70 00 5c 00 00 ff 32 91 40 0a 6f 0a c5
        0a 6f 0a 1d 51 46 53 6b 00 00 00 10 00 00 01 00
        01 00 00 00 78 0a 2c 62 62 32 15 7b fe 01 76 32
        f3 2d b4 d0 a4 fa 61 2f 66 c2 bf 79 d5 e2 14 9b
        ac 1d fc 4b 15 4b 69 03 4d c2 1d ef 20 90 6d 59
        62 81 12 7c ff 72 56 ab f0 0b a1 22 bb 5e 6c 71
        a4 d4 9a 4d c2 2f 87 40 83 8e 3d fa ce 91 cc b8
```

3. ENCR_MAGMA_MGM_KTREE (Example 1):

```
    transform key [36]:
        5b 50 bf 33 78 87 02 38 f3 ca 74 0f d1 24 ba 6c
        22 83 ef 58 9b e6 f4 6a 89 4a a3 5d 5f 06 b2 03
        cf 36 63 12
    K [32]:
        5b 50 bf 33 78 87 02 38 f3 ca 74 0f d1 24 ba 6c
        22 83 ef 58 9b e6 f4 6a 89 4a a3 5d 5f 06 b2 03
    salt [4]:
```

```
        cf 36 63 12
    i1 = 00, i2 = 0000, i3 = 0000, pnum = 000000
    K_msg [32]:
        25 65 21 e2 70 b7 4a 16 4d fc 26 e6 bf 0c ca 76
        5e 9d 41 02 7d 4b 7b 19 76 2b 1c c9 01 dc de 7f
    nonce [8]:
        00 00 00 00 cf 36 63 12
    IV [8]:
        00 00 00 00 00 00 00 00
    AAD [8]:
        c8 c2 b2 8d 00 00 00 01
    plaintext [64]:
        45 00 00 3c 24 2d 00 00 7f 01 ed d4 0a 6f 0a c5
        0a 6f 0a 1d 08 00 de 5b 02 00 6d 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
    ciphertext [64]:
        fa 08 40 33 2c 4f 3f c9 64 4d 8c 2c 4a 91 7e 0c
        d8 6f 8e 61 04 03 87 64 6b b9 df bd 91 50 3f 4a
        f5 d2 42 69 49 d3 5a 22 9e 1e 0e fc 99 ac ee 9e
        32 43 e2 3b a4 d1 1e 84 5c 91 a7 19 15 52 cc e8
    ESP ICV [8]:
        5f 4a fa 8b 02 94 0f 5c
    ESP packet [108]:
        45 00 00 6c 00 62 00 00 ff 32 91 3e 0a 6f 0a c5
        0a 6f 0a 1d c8 c2 b2 8d 00 00 00 01 00 00 00 00
        00 00 00 00 fa 08 40 33 2c 4f 3f c9 64 4d 8c 2c
        4a 91 7e 0c d8 6f 8e 61 04 03 87 64 6b b9 df bd
        91 50 3f 4a f5 d2 42 69 49 d3 5a 22 9e 1e 0e fc
        99 ac ee 9e 32 43 e2 3b a4 d1 1e 84 5c 91 a7 19
        15 52 cc e8 5f 4a fa 8b 02 94 0f 5c
```

4.   ENCR_MAGMA_MGM_KTREE (Example 2):

```
    transform key [36]:
        5b 50 bf 33 78 87 02 38 f3 ca 74 0f d1 24 ba 6c
        22 83 ef 58 9b e6 f4 6a 89 4a a3 5d 5f 06 b2 03
        cf 36 63 12
    K [32]:
        5b 50 bf 33 78 87 02 38 f3 ca 74 0f d1 24 ba 6c
        22 83 ef 58 9b e6 f4 6a 89 4a a3 5d 5f 06 b2 03
    salt [4]:
        cf 36 63 12
    i1 = 00, i2 = 0001, i3 = 0001, pnum = 000000
    K_msg [32]:
        20 e0 46 d4 09 83 9b 23 f0 66 a5 0a 7a 06 5b 4a
        39 24 4f 0e 29 ef 1e 6f 2e 5d 2e 13 55 f5 da 08
    nonce [8]:
        00 00 00 00 cf 36 63 12
    IV [8]:
        00 00 01 00 01 00 00 00
    AAD [8]:
        c8 c2 b2 8d 00 00 00 10
    plaintext [64]:
        45 00 00 3c 24 40 00 00 7f 01 ed c1 0a 6f 0a c5
        0a 6f 0a 1d 08 00 cf 5b 02 00 7c 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
    ciphertext [64]:
        7a 71 48 41 a5 34 b7 58 93 6a 8e ab 26 91 40 a8
        25 a7 f3 5d b9 e4 37 1f e7 6c 99 9c 9b 88 db 72
        1d c7 59 f6 56 b5 b3 ea b6 b1 4d 6b d7 7a 07 1d
        4b 93 78 bd 08 97 6c 33 ed 9a 01 91 bf fe a1 dd
    ESP ICV [8]:
        dd 5d 50 9a fd b8 09 98
    ESP packet [108]:
        45 00 00 6c 00 71 00 00 ff 32 91 2f 0a 6f 0a c5
        0a 6f 0a 1d c8 c2 b2 8d 00 00 00 10 00 00 01 00
        01 00 00 00 7a 71 48 41 a5 34 b7 58 93 6a 8e ab
        26 91 40 a8 25 a7 f3 5d b9 e4 37 1f e7 6c 99 9c
        9b 88 db 72 1d c7 59 f6 56 b5 b3 ea b6 b1 4d 6b
```

```
        d7 7a 07 1d 4b 93 78 bd 08 97 6c 33 ed 9a 01 91
        bf fe a1 dd dd 5d 50 9a fd b8 09 98
```

5. ENCR_KUZNYECHIK_MGM_MAC_KTREE (Example 1):

```
    transform key [44]:
        98 bd 34 ce 3b e1 9a 34 65 e4 87 c0 06 48 83 f4
        88 cc 23 92 63 dc 32 04 91 9b 64 3f e7 57 b2 be
        6c 51 cb ac 93 c4 5b ea 99 62 79 1d
    K [32]:
        98 bd 34 ce 3b e1 9a 34 65 e4 87 c0 06 48 83 f4
        88 cc 23 92 63 dc 32 04 91 9b 64 3f e7 57 b2 be
    salt [12]:
        6c 51 cb ac 93 c4 5b ea 99 62 79 1d
    i1 = 00, i2 = 0000, i3 = 0000, pnum = 000000
    K_msg [32]:
        98 f1 03 01 81 0a 04 1c da dd e1 bd 85 a0 8f 21
        8b ac b5 7e 00 35 e2 22 c8 31 e3 e4 f0 a2 0c 8f
    nonce [16]:
        00 00 00 00 6c 51 cb ac 93 c4 5b ea 99 62 79 1d
    IV [8]:
        00 00 00 00 00 00 00 00
    AAD [80]:
        3d ac 92 6a 00 00 00 01 00 00 00 00 00 00 00 00
        45 00 00 3c 0c f1 00 00 7f 01 05 11 0a 6f 0a c5
        0a 6f 0a 1d 08 00 48 5c 02 00 03 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
    plaintext [0]:
    ciphertext [0]:
    ESP ICV [12]:
        ca c5 8c e5 e8 8b 4b f3 2d 6c f0 4d
    ESP packet [112]:
        45 00 00 70 00 01 00 00 ff 32 91 9b 0a 6f 0a c5
        0a 6f 0a 1d 3d ac 92 6a 00 00 00 01 00 00 00 00
        00 00 00 00 45 00 00 3c 0c f1 00 00 7f 01 05 11
        0a 6f 0a c5 0a 6f 0a 1d 08 00 48 5c 02 00 03 00
        61 62 63 64 65 66 67 68 69 6a 6b 6c 6d 6e 6f 70
        71 72 73 74 75 76 77 61 62 63 64 65 66 67 68 69
        01 02 02 04 ca c5 8c e5 e8 8b 4b f3 2d 6c f0 4d
```

6. ENCR_KUZNYECHIK_MGM_MAC_KTREE (Example 2):

```
    transform key [44]:
        98 bd 34 ce 3b e1 9a 34 65 e4 87 c0 06 48 83 f4
        88 cc 23 92 63 dc 32 04 91 9b 64 3f e7 57 b2 be
        6c 51 cb ac 93 c4 5b ea 99 62 79 1d
    K [32]:
        98 bd 34 ce 3b e1 9a 34 65 e4 87 c0 06 48 83 f4
        88 cc 23 92 63 dc 32 04 91 9b 64 3f e7 57 b2 be
    salt [12]:
        6c 51 cb ac 93 c4 5b ea 99 62 79 1d
    i1 = 00, i2 = 0000, i3 = 0001, pnum = 000000
    K_msg [32]:
        02 c5 41 87 7c c6 23 f3 f1 35 91 9a 75 13 b6 f8
        a8 a1 8c b2 63 99 86 2f 50 81 4f 52 91 01 67 84
    nonce [16]:
        00 00 00 00 6c 51 cb ac 93 c4 5b ea 99 62 79 1d
    IV [8]:
        00 00 00 00 01 00 00 00
    AAD [80]:
        3d ac 92 6a 00 00 00 06 00 00 00 00 01 00 00 00
        45 00 00 3c 0c fb 00 00 7f 01 05 07 0a 6f 0a c5
        0a 6f 0a 1d 08 00 43 5c 02 00 08 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
    plaintext [0]:
    ciphertext [0]:
    ESP ICV [12]:
        ba bc 67 ec 72 a8 c3 1a 89 b4 0e 91
    ESP packet [112]:
```

```
        45 00 00 70 00 06 00 00 ff 32 91 96 0a 6f 0a c5
        0a 6f 0a 1d 3d ac 92 6a 00 00 00 06 00 00 00 00
        01 00 00 00 45 00 00 3c 0c fb 00 00 7f 01 05 07
        0a 6f 0a c5 0a 6f 0a 1d 08 00 43 5c 02 00 08 00
        61 62 63 64 65 66 67 68 69 6a 6b 6c 6d 6e 6f 70
        71 72 73 74 75 76 77 61 62 63 64 65 66 67 68 69
        01 02 02 04 ba bc 67 ec 72 a8 c3 1a 89 b4 0e 91
```

7. ENCR_MAGMA_MGM_MAC_KTREE (Example 1):

```
    transform key [36]:
        d0 65 b5 30 fa 20 b8 24 c7 57 0c 1d 86 2a e3 39
        2c 1c 07 6d fa da 69 75 74 4a 07 a8 85 7d bd 30
        88 79 8f 29
    K [32]:
        d0 65 b5 30 fa 20 b8 24 c7 57 0c 1d 86 2a e3 39
        2c 1c 07 6d fa da 69 75 74 4a 07 a8 85 7d bd 30
    salt [4]:
        88 79 8f 29
    i1 = 00, i2 = 0000, i3 = 0000, pnum = 000000
    K_msg [32]:
        4c 61 45 99 a0 a0 67 f1 94 87 24 0a e1 00 e1 b7
        ea f2 3e da f8 7e 38 73 50 86 1c 68 3b a4 04 46
    nonce [8]:
        00 00 00 00 88 79 8f 29
    IV [8]:
        00 00 00 00 00 00 00 00
    AAD [80]:
        3e 40 69 9c 00 00 00 01 00 00 00 00 00 00 00 00
        45 00 00 3c 0e 08 00 00 7f 01 03 fa 0a 6f 0a c5
        0a 6f 0a 1d 08 00 36 5c 02 00 15 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
    plaintext [0]:
    ciphertext [0]:
    ESP ICV [8]:
        4d d4 25 8a 25 35 95 df
    ESP packet [108]:
        45 00 00 6c 00 13 00 00 ff 32 91 8d 0a 6f 0a c5
        0a 6f 0a 1d 3e 40 69 9c 00 00 00 01 00 00 00 00
        00 00 00 00 45 00 00 3c 0e 08 00 00 7f 01 03 fa
        0a 6f 0a c5 0a 6f 0a 1d 08 00 36 5c 02 00 15 00
        61 62 63 64 65 66 67 68 69 6a 6b 6c 6d 6e 6f 70
        71 72 73 74 75 76 77 61 62 63 64 65 66 67 68 69
        01 02 02 04 4d d4 25 8a 25 35 95 df
```

8. ENCR_MAGMA_MGM_MAC_KTREE (Example 2):

```
    transform key [36]:
        d0 65 b5 30 fa 20 b8 24 c7 57 0c 1d 86 2a e3 39
        2c 1c 07 6d fa da 69 75 74 4a 07 a8 85 7d bd 30
        88 79 8f 29
    K [32]:
        d0 65 b5 30 fa 20 b8 24 c7 57 0c 1d 86 2a e3 39
        2c 1c 07 6d fa da 69 75 74 4a 07 a8 85 7d bd 30
    salt [4]:
        88 79 8f 29
    i1 = 00, i2 = 0000, i3 = 0001, pnum = 000000
    K_msg [32]:
        b4 f3 f9 0d c4 87 fa b8 c4 af d0 eb 45 49 f2 f0
        e4 36 32 b6 79 19 37 2e 1e 96 09 ea f0 b8 e2 28
    nonce [8]:
        00 00 00 00 88 79 8f 29
    IV [8]:
        00 00 00 00 01 00 00 00
    AAD [80]:
        3e 40 69 9c 00 00 00 06 00 00 00 00 01 00 00 00
        45 00 00 3c 0e 13 00 00 7f 01 03 ef 0a 6f 0a c5
        0a 6f 0a 1d 08 00 31 5c 02 00 1a 00 61 62 63 64
        65 66 67 68 69 6a 6b 6c 6d 6e 6f 70 71 72 73 74
        75 76 77 61 62 63 64 65 66 67 68 69 01 02 02 04
```

```
   plaintext [0]:
   ciphertext [0]:
   ESP ICV [8]:
       84 84 a9 23 30 a0 b1 96
   ESP packet [108]:
       45 00 00 6c 00 18 00 00 ff 32 91 88 0a 6f 0a c5
       0a 6f 0a 1d 3e 40 69 9c 00 00 00 06 00 00 00 00
       01 00 00 00 45 00 00 3c 0e 13 00 00 7f 01 03 ef
       0a 6f 0a c5 0a 6f 0a 1d 08 00 31 5c 02 00 1a 00
       61 62 63 64 65 66 67 68 69 6a 6b 6c 6d 6e 6f 70
       71 72 73 74 75 76 77 61 62 63 64 65 66 67 68 69
       01 02 02 04 84 84 a9 23 30 a0 b1 96
```

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