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ChaCha20, Poly1305, and Their Use in the Internet Key Exchange Protocol (IKE) and IPsec

Abstract

This document describes the use of the ChaCha20 stream cipher along with the Poly1305 authenticator, combined into an AEAD algorithm for the Internet Key Exchange Protocol version 2 (IKEv2) and for IPsec.

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1. Introduction

The Advanced Encryption Standard (AES) [FIPS-197] has become the go-to algorithm for encryption. It is now the most commonly used algorithm in many areas, including IPsec Virtual Private Networks (VPNs). On most modern platforms, AES is anywhere from four to ten times as fast as the previously popular cipher, Triple Data Encryption Standard (3DES) [SP800-67]. 3DES also uses a 64-bit block; this means that the amount of data that can be encrypted before rekeying is required is limited. These reasons make AES not only the best choice, but the only viable choice for IPsec.

The problem is that if future advances in cryptanalysis reveal a weakness in AES, VPN users will be in an unenviable position. With the only other widely supported cipher for IPsec implementations being the much slower 3DES, it is not feasible to reconfigure IPsec installations away from AES. [Standby-Cipher] describes this issue and the need for a standby cipher in greater detail.

This document proposes the fast and secure ChaCha20 stream cipher as such a standby cipher in an Authenticated Encryption with Associated Data (AEAD) construction with the Poly1305 authenticator for use with the Encapsulated Security Protocol (ESP) [RFC4303] and the Internet Key Exchange Protocol version 2 (IKEv2) [RFC7296]. The algorithms are described in a separate document ([RFC7539]). This document only describes the IPsec-specific things.

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 [RFC2119].

2. ChaCha20 and Poly1305 for ESP

AEAD_CHACHA20_POLY1305 ([RFC7539]) is a combined mode algorithm, or AEAD. Usage follows the AEAD construction in Section 2.8 of RFC 7539:

- o The Initialization Vector (IV) is 64 bits and is used as part of the nonce. The IV MUST be unique for each invocation for a particular security association (SA) but does not need to be unpredictable. The use of a counter or a linear feedback shift register (LFSR) is RECOMMENDED.

- o A 32-bit Salt is prepended to the 64-bit IV to form the 96-bit nonce. The salt is fixed per SA, and it is not transmitted as part of the ESP packet.

- o The encryption key is 256 bits.

- o The Internet Key Exchange Protocol generates a bitstring called KEYMAT using a pseudorandom function (PRF). That KEYMAT is divided into keys for encryption, message authentication, and whatever else is needed. The KEYMAT requested for each ChaCha20-Poly1305 key is 36 octets. The first 32 octets are the 256-bit ChaCha20 key, and the remaining 4 octets are used as the Salt value in the nonce.

The ChaCha20 encryption algorithm requires the following parameters: a 256-bit key, a 96-bit nonce, and a 32-bit Initial Block Counter. For ESP, we set these as follows:

- o The key is set as mentioned above.

- o The 96-bit nonce is formed from a concatenation of the 32-bit Salt and the 64-bit IV, as described above.

- o The Initial Block Counter is set to one (1). The reason that one is used for the initial counter rather than zero is that zero is reserved for generating the one-time Poly1305 key (see below).

As the ChaCha20 block function is not applied directly to the plaintext, no padding should be necessary. However, in keeping with the specification in RFC 4303, the plaintext always has a pad length octet and a Next Header octet, and it may require padding octets so as to align the buffer to an integral multiple of 4 octets.

The same key and nonce, along with a block counter of zero, are passed to the ChaCha20 block function, and the top 256 bits of the result are used as the Poly1305 key.

Finally, the Poly1305 function is run on the data to be authenticated, which is, as specified in Section 2.8 of [RFC7539], a concatenation of the following in the order below:

- The Authenticated Additional Data (AAD); see Section 2.1.
- Zero-octet padding that rounds the length up to 16 octets. This is 4 or 8 octets depending on the length of the AAD.
- The ciphertext.
- Zero-octet padding that rounds the total length up to an integral multiple of 16 octets.
- The length of the AAD in octets (as a 64-bit integer encoded in little-endian byte order).
- The length of the ciphertext in octets (as a 64-bit integer encoded in little-endian byte order).

The 128-bit output of Poly1305 is used as the tag. All 16 octets are included in the packet.

The figure below is a copy of Figure 2 in RFC 4303:

```
  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
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |               Security Parameters Index (SPI)                 |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                      Sequence Number                          |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+---
 |                    IV (optional)                              | ^ p
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ | a
 |                    Rest of Payload Data  (variable)           | | y
 ~                                                               ~ | l
 |                                                               | | o
 +               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ | a
 |               |         TFC Padding * (optional, variable)    | v d
 +-+-+-+-+-+-+-+-+         +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+---
 |                         |        Padding (0-255 bytes)        |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+     +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                               |  Pad Length   | Next Header   |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |         Integrity Check Value-ICV   (variable)                |
 ~                                                               ~
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- The IV field is 64 bits. It is the final 64 bits of the 96-bit nonce. If the counter method is used for generating unique IVs, then the final 32 bits of the IV will be equal to the Sequence Number field.

- The length of the Padding field need not exceed 4 octets. However, neither RFC 4303 nor this specification require using the minimal padding length.

- The Integrity Check Value field contains the 16-octet tag.

2.1. AAD Construction

The construction of the Additional Authenticated Data (AAD) is similar to the one in [RFC4106]. For security associations (SAs) with 32-bit sequence numbers, the AAD is 8 octets: a 4-octet SPI followed by a 4-octet sequence number ordered exactly as it is in the packet. For SAs with an Extended Sequence Number (ESN), the AAD is 12 octets: a 4-octet SPI followed by an 8-octet sequence number as a 64-bit integer in big-endian byte order.

3. Use in IKEv2

AEAD algorithms can be used in IKE, as described in [RFC5282]. More specifically:

- o The Encrypted Payload is as described in Section 3 of RFC 5282.
- o The ChaCha20-Poly1305 keying material is derived similarly to ESP: 36 octets are requested for each of SK_ei and SK_er, of which the first 32 form the key and the last 4 form the salt. No octets are requested for SK_ai and SK_ar.
- o The IV is 64 bits, as described in Section 2, and is included explicitly in the Encrypted payload.
- o The sender SHOULD include no padding and set the Pad Length field to zero. The receiver MUST accept any length of padding.
- o The AAD is as described in Section 5.1 of RFC 5282, so it is 32 octets (28 for the IKEv2 header plus 4 octets for the encrypted payload header), assuming no unencrypted payloads.

4. Negotiation in IKEv2

When negotiating the ChaCha20-Poly1305 algorithm for use in IKE or IPsec, the value ENCR_CHACHA20_POLY1305 (28) should be used in the transform substructure of the SA payload as the ENCR (type 1) transform ID. As with other AEAD algorithms, INTEG (type 3) transform substructures MUST NOT be specified, or just one INTEG transform MAY be included with value NONE (0).

5. Security Considerations

The ChaCha20 cipher is designed to provide 256-bit security.

The Poly1305 authenticator is designed to ensure that forged messages are rejected with a probability of 1-(n/(2^102)) for a 16n-octet message, even after sending 2^64 legitimate messages, so it is SUF-CMA (strong unforgeability against chosen-message attacks) in the terminology of [AE].

The most important security consideration in implementing this document is the uniqueness of the nonce used in ChaCha20. The nonce should be selected uniquely for a particular key, but unpredictability of the nonce is not required. Counters and LFSRs are both acceptable ways of generating unique nonces.

Another issue with implementing these algorithms is avoiding side channels. This is trivial for ChaCha20, but requires some care for Poly1305. Considerations for implementations of these algorithms are in [RFC7539].

The Salt value in used nonce construction in ESP and IKEv2 is derived from the keystream, same as the encryption key. It is never transmitted on the wire, but the security of the algorithm does not depend on its secrecy. Thus, implementations that keep keys and other secret material within some security boundary MAY export the Salt from the security boundary. This may be useful if the API provided by the library accepts the nonce as a parameter rather than the IV.

6. IANA Considerations

IANA has assigned the value 28 as a transform identifier for the algorithm described in this document in the "Transform Type 1 - Encryption Algorithm Transform IDs" registry with name ENCR_CHACHA20_POLY1305 and this document as reference for both ESP and IKEv2.

7. References

7.1. Normative References

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[RFC4303] Kent, S., "IP Encapsulating Security Payload (ESP)", RFC 4303, DOI 10.17487/RFC4303, December 2005, <http://www.rfc-editor.org/info/rfc4303>.

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7.2. Informative References

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[RFC1761] Callaghan, B. and R. Gilligan, "Snoop Version 2 Packet Capture File Format", RFC 1761, DOI 10.17487/RFC1761, February 1995, <http://www.rfc-editor.org/info/rfc1761>.

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[SP800-67] National Institute of Standards and Technology, "Recommendation for the Triple Data Encryption Algorithm (TDEA) Block Cipher", FIPS SP800-67, January 2012, <http://csrc.nist.gov/publications/nistpubs/800-67-Rev1/SP-800-67-Rev1.pdf>.

[Standby-Cipher] McGrew, D., Grieco, A., and Y. Sheffer, "Selection of Future Cryptographic Standards", Work in Progress draft-mcgrew-standby-cipher-00, January 2013.

Appendix A. ESP Example

For this example, we will use a tunnel-mode ESP SA using the ChaCha20-Poly1305 algorithm. The keying material is as follows:

```
KEYMAT:
000  80 81 82 83 84 85 86 87 88 89 8a 8b 8c 8d 8e 8f  ................
016  90 91 92 93 94 95 96 97 98 99 9a 9b 9c 9d 9e 9f  ................
032  a0 a1 a2 a3                                      ....
```

Obviously not a great PRF. The first 32 octets are the key and the final 4 octets (0xa0 0xa1 0xa2 0xa3) are the salt. For the packet, we will use an ICMP packet from 198.51.100.5 to 192.0.2.5:

```
Source Packet:
000  45 00 00 54 a6 f2 00 00 40 01 e7 78 c6 33 64 05  E..T....@..x.3d.
016  c0 00 02 05 08 00 5b 7a 3a 08 00 00 55 3b ec 10  ......[z:...U;..
032  00 07 36 27 08 09 0a 0b 0c 0d 0e 0f 10 11 12 13  ..6'............
048  14 15 16 17 18 19 1a 1b 1c 1d 1e 1f 20 21 22 23  ............ !"#
064  24 25 26 27 28 29 2a 2b 2c 2d 2e 2f 30 31 32 33  $%&'()*+,-./0123
080  34 35 36 37                                      4567
```

The SA details are as follows:

- The key and Salt are as above.
- The SPI is 0x01 0x02 0x03 0x04.
- The next sequence number is 5; ESN is not enabled.
- The gateway IP address for this side is 203.0.113.153; The peer address is 203.0.113.5.
- NAT was not detected.

The 64-bit IV is 0x10 0x11 0x12 0x13 0x14 0x15 0x16 0x17. Putting together the salt and IV we get the nonce:

```
The nonce:
000  a0 a1 a2 a3 10 11 12 13 14 15 16 17              ............
```

The plaintext to encrypt consists of the source IP packet plus the padding:

```
Plaintext (includes padding and pad length):
000  45 00 00 54 a6 f2 00 00 40 01 e7 78 c6 33 64 05  E..T....@..x.3d.
016  c0 00 02 05 08 00 5b 7a 3a 08 00 00 55 3b ec 10  ......[z:...U;..
032  00 07 36 27 08 09 0a 0b 0c 0d 0e 0f 10 11 12 13  ..6'............
048  14 15 16 17 18 19 1a 1b 1c 1d 1e 1f 20 21 22 23  ............ !"#
064  24 25 26 27 28 29 2a 2b 2c 2d 2e 2f 30 31 32 33  $%&'()*+,-./0123
080  34 35 36 37 01 02 02 04                          4567....
```

With the key, nonce, and plaintext available, we can call the ChaCha20 function and encrypt the packet, producing the ciphertext:

```
Ciphertext:
000  24 03 94 28 b9 7f 41 7e 3c 13 75 3a 4f 05 08 7b  $..(..A~<.u:O..{
016  67 c3 52 e6 a7 fa b1 b9 82 d4 66 ef 40 7a e5 c6  g.R.......f.@z..
032  14 ee 80 99 d5 28 44 eb 61 aa 95 df ab 4c 02 f7  .....(D.a....L..
048  2a a7 1e 7c 4c 4f 64 c9 be fe 2f ac c6 38 e8 f3  *..|LOd.../..8..
064  cb ec 16 3f ac 46 9b 50 27 73 f6 fb 94 e6 64 da  ...?.F.P's....d.
080  91 65 b8 28 29 f6 41 e0                          .e.().A.
```

To calculate the tag, we need a one-time Poly1305 key, which we calculate by calling the ChaCha20 function again with the same key and nonce, but a block count of zero.

```
Poly1305 one-time key:
000  af 1f 41 2c c1 15 ad ce 5e 4d 0e 29 d5 c1 30 bf  ..A,....^M.)..0.
016  46 31 21 0e 0f ef 74 31 c0 45 4f e7 0f d7 c2 d1  F1!...t1.EO.....
```

The AAD is constructed by concatenating the SPI to the sequence number:

```
000  01 02 03 04 00 00 00 05                          ........
```

The input to the Poly1305 function is constructed by concatenating and padding the AAD and ciphertext:

```
Poly1305 Input:
000  01 02 03 04 00 00 00 05 00 00 00 00 00 00 00 00  ................
016  24 03 94 28 b9 7f 41 7e 3c 13 75 3a 4f 05 08 7b  $..(..A~<.u:O..{
032  67 c3 52 e6 a7 fa b1 b9 82 d4 66 ef 40 7a e5 c6  g.R.......f.@z..
048  14 ee 80 99 d5 28 44 eb 61 aa 95 df ab 4c 02 f7  .....(D.a....L..
064  2a a7 1e 7c 4c 4f 64 c9 be fe 2f ac c6 38 e8 f3  *..|LOd.../..8..
080  cb ec 16 3f ac 46 9b 50 27 73 f6 fb 94 e6 64 da  ...?.F.P's....d.
096  91 65 b8 28 29 f6 41 e0 00 00 00 00 00 00 00 00  .e.().A.........
112  08 00 00 00 00 00 00 00 58 00 00 00 00 00 00 00  ........X.......
```

The resulting tag is:

```
Tag:
000  76 aa a8 26 6b 7f b0 f7 b1 1b 36 99 07 e1 ad 43  v..&k.....6....C
```

Putting it all together, the resulting packet is as follows:

```
ESP packet:
000  45 00 00 8c 23 45 00 00 40 32 de 5b cb 00 71 99  E...#E..@2.[..q.
016  cb 00 71 05 01 02 03 04 00 00 00 05 10 11 12 13  ..q.............
032  14 15 16 17 24 03 94 28 b9 7f 41 7e 3c 13 75 3a  ....$..(..A~<.u:
048  4f 05 08 7b 67 c3 52 e6 a7 fa b1 b9 82 d4 66 ef  O..{g.R.......f.
064  40 7a e5 c6 14 ee 80 99 d5 28 44 eb 61 aa 95 df  @z.......(D.a...
080  ab 4c 02 f7 2a a7 1e 7c 4c 4f 64 c9 be fe 2f ac  .L..*..|LOd.../.
096  c6 38 e8 f3 cb ec 16 3f ac 46 9b 50 27 73 f6 fb  .8.....?.F.P's..
112  94 e6 64 da 91 65 b8 28 29 f6 41 e0 76 aa a8 26  ..d..e.().A.v..&
128  6b 7f b0 f7 b1 1b 36 99 07 e1 ad 43              k.....6....C
```

Appendix B. IKEv2 Example

For the IKEv2 example, we'll use the following:

- o The key is 0x80..0x9f, the same as in Appendix A.
- o The Salt is 0xa0 0xa1 0xa2 0xa3.
- o The IV will also be the same as in the previous example. The fact that the IV and Salt are both the same means that the nonce is also the same.
- o Because the key and nonce are the same, so is the one-time Poly1305 key.
- o The packet will be an INFORMATIONAL request carrying a single payload: a Notify payload with type SET_WINDOW_SIZE, setting the window size to 10.
- o iSPI = 0xc0 0xc1 0xc2 0xc3 0xc4 0xc5 0xc6 0xc7.
- o rSPI = 0xd0 0xd1 0xd2 0xd3 0xd4 0xd5 0xd6 0xd7.
- o Message ID shall be 9.

```
The Notify Payload:
000  00 00 00 0c 00 00 40 01 00 00 00 0a            ......@.....

Plaintext (with no padding and a zero pad length):
000  00 00 00 0c 00 00 40 01 00 00 00 0a 00         ......@......
```

```
Ciphertext:
000  61 03 94 70 1f 8d 01 7f 7c 12 92 48 89          a..p....|..H.
```

The AAD is constructed by appending the IKE header to the encrypted payload header. Note that the length field in the IKE header and the length field in the encrypted payload header have to be calculated before constructing the AAD:

```
AAD:
000  c0 c1 c2 c3 c4 c5 c6 c7 d0 d1 d2 d3 d4 d5 d6 d7  ................
016  2e 20 25 00 00 00 00 09 00 00 00 45 29 00 00 29  . %........E)..)
```

In this case, the length of the AAD is an integral multiple of 16, so when constructing the input to Poly1305 there was no need for padding. The ciphertext is 13 octets long, so it is followed by 3 zero octets. The input to Poly1305 is 32 octets of AAD, 13 octets of ciphertext, 3 octets of zero padding, and two 8-octet length fields in little-endian byte order.

```
Poly1305 Input:
000  c0 c1 c2 c3 c4 c5 c6 c7 d0 d1 d2 d3 d4 d5 d6 d7  ................
016  2e 20 25 00 00 00 00 09 00 00 00 45 29 00 00 29  . %........E)..)
032  61 03 94 70 1f 8d 01 7f 7c 12 92 48 89 00 00 00  a..p....|..H....
048  20 00 00 00 00 00 00 00 0d 00 00 00 00 00 00 00   ...............

Tag:
000  6b 71 bf e2 52 36 ef d7 cd c6 70 66 90 63 15 b2  kq..R6....pf.c..

Encrypted Payload:
000  29 00 00 29 10 11 12 13 14 15 16 17 61 03 94 70  )..)........a..p
016  1f 8d 01 7f 7c 12 92 48 89 6b 71 bf e2 52 36 ef  ....|..H.kq..R6.
032  d7 cd c6 70 66 90 63 15 b2                       ...pf.c..

The IKE Message:
000  c0 c1 c2 c3 c4 c5 c6 c7 d0 d1 d2 d3 d4 d5 d6 d7  ................
016  2e 20 25 00 00 00 00 09 00 00 00 45 29 00 00 29  . %........E)..)
032  10 11 12 13 14 15 16 17 61 03 94 70 1f 8d 01 7f  ........a..p....
048  7c 12 92 48 89 6b 71 bf e2 52 36 ef d7 cd c6 70  |..H.kq..R6....p
064  66 90 63 15 b2                                   f.c..
```

The below file in the snoop format [RFC1761] contains three packets: The first is the ICMP packet from the example in Appendix A, the second is the ESP packet from the same appendix, and the third is the IKEv2 packet from this appendix. To convert this text back into a file, you can use a Unix command line tool such as "openssl enc -d -a":


```
c25vb3AAAAAAAAACAAAABAAAAGIAAABiAAAAegAAAABVPq8PAAADVdhs6fUQBHgx
wbcpwggARQAAVKbyAABAAed4xjNkBcAAAgUIAFt6OggAAFU77BAABzYnCAkKCwwN
Dg8QERITFBUWFxgZGhscHR4fICEiIyQlJicoKSorLC0uLzAxMjM0NTY3AAAAmgAA
AJoAAACyAAAAAFU+rw8AAAo62Gzp9RAEeDHBtynCCABFAACMI0UAAEAy3lvLAHGZ
ywBxBQECAwQAAAAFEBESExQVFhckA5QouX9BfjwTdTpPBQh7Z8NS5qf6sbmC1Gbv
QHrlxhTugJnVKETrYaqV36tMAvcqpx58TE9kyb7+L6zGOOjzy+wWP6xGm1Anc/b7
lOZk2pFluCgp9kHgdqqoJmt/sPexGzaZB+GtQwAAAG8AAABvAAAAhwAAAABVPq8P
AAARH9hs6fUQBHgxwbcpwggARQAAYSNFAABAEd6nywBxmcsAcQUB9AH0AE0IUcDB
wsPExcbH0NHS09TV1tcuICUAAAAACQAAAEUpAAApEBESExQVFhdhA5RwH40Bf3wS
kkiJa3G/4lI279fNxnBmkGMVsg==
```


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