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Using HMAC-SHA-256, HMAC-SHA-384, and HMAC-SHA-512 with IPsec

Status of This Memo

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Abstract

This specification describes the use of Hashed Message Authentication Mode (HMAC) in conjunction with the SHA-256, SHA-384, and SHA-512 algorithms in IPsec. These algorithms may be used as the basis for data origin authentication and integrity verification mechanisms for the Authentication Header (AH), Encapsulating Security Payload (ESP), Internet Key Exchange Protocol (IKE), and IKEv2 protocols, and also as Pseudo-Random Functions (PRFs) for IKE and IKEv2. Truncated output lengths are specified for the authentication-related variants, with the corresponding algorithms designated as HMAC-SHA-256-128, HMAC-SHA-384-192, and HMAC-SHA-512-256. The PRF variants are not truncated, and are called PRF-HMAC-SHA-256, PRF-HMAC-SHA-384, and PRF-HMAC-SHA-512.

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1. Introduction

This document specifies the use of SHA-256, SHA-384, and SHA-512 [SHA2-1] combined with HMAC [HMAC] as data origin authentication and integrity verification mechanisms for the IPsec AH [AH], ESP [ESP], IKE [IKE], and IKEv2 [IKEv2] protocol. Output truncation is specified for these variants, with the corresponding algorithms designated as HMAC-SHA-256-128, HMAC-SHA-384-192, and HMAC-SHA-512-256. These truncation lengths are chosen in accordance with the birthday bound for each algorithm.

This specification also describes untruncated variants of these algorithms as Pseudo-Random Functions (PRFs) for use with IKE and IKEv2, and those algorithms are called PRF-HMAC-SHA-256, PRF-HMAC-SHA-384, and PRF-HMAC-SHA-512. For ease of reference, these PRF algorithms and the authentication variants described above are collectively referred to below as "the HMAC-SHA-256+ algorithms".

The goal of the PRF variants are to provide secure pseudo-random functions suitable for generation of keying material and other protocol-specific numeric quantities, while the goal of the authentication variants is to ensure that packets are authentic and cannot be modified in transit. The relative security of HMAC-SHA-256+ when used in either case is dependent on the distribution scope and unpredictability of the associated secret key. If the key is unpredictable and known only by the sender and recipient, these algorithms ensure that only parties holding an identical key can derive the associated values.

2. The HMAC-SHA-256+ Algorithms

[SHA2-1] and [SHA2-2] describe the underlying SHA-256, SHA-384, and SHA-512 algorithms, while [HMAC] describes the HMAC algorithm. The HMAC algorithm provides a framework for inserting various hashing algorithms such as SHA-256, and [SHA256+] describes combined usage of these algorithms. The following sections describe the various characteristics and requirements of the HMAC-SHA-256+ algorithms when used with IPsec.

2.1. Keying Material

Requirements for keying material vary depending on whether the algorithm is functioning as a PRF or as an authentication/integrity mechanism. In the case of authentication/integrity, key lengths are fixed according to the output length of the algorithm in use. In the

case of PRFs, key lengths are variable, but guidance is given to ensure interoperability. These distinctions are described further below.

Before describing key requirements for each usage, it is important to clarify some terms we use below:

Block size: the size of the data block the underlying hash algorithm operates upon. For SHA-256, this is 512 bits, for SHA-384 and SHA-512, this is 1024 bits.

Output length: the size of the hash value produced by the underlying hash algorithm. For SHA-256, this is 256 bits, for SHA-384 this is 384 bits, and for SHA-512, this is 512 bits.

Authenticator length: the size of the "authenticator" in bits. This only applies to authentication/integrity related algorithms, and refers to the bit length remaining after truncation. In this specification, this is always half the output length of the underlying hash algorithm.

2.1.1. Data Origin Authentication and Integrity Verification Usage

HMAC-SHA-256+ are secret key algorithms. While no fixed key length is specified in [HMAC], this specification requires that when used as an integrity/authentication algorithm, a fixed key length equal to the output length of the hash functions **MUST** be supported, and key lengths other than the output length of the associated hash function **MUST NOT** be supported.

These key length restrictions are based in part on the recommendations in [HMAC] (key lengths less than the output length decrease security strength, and keys longer than the output length do not significantly increase security strength), and in part because allowing variable length keys for IPsec authenticator functions would create interoperability issues.

2.1.2. Pseudo-Random Function (PRF) Usage

IKE and IKEv2 use PRFs for generating keying material and for authentication of the IKE Security Association. The IKEv2 specification differentiates between PRFs with fixed key sizes and those with variable key sizes, and so we give some special guidance for this below.

When a PRF described in this document is used with IKE or IKEv2, it is considered to have a variable key length, and keys are derived in the following ways (note that we simply reiterate that which is specified in [HMAC]):

- o If the length of the key is exactly the algorithm block size, use it as-is.
- o If the key is shorter than the block size, lengthen it to exactly the block size by padding it on the right with zero bits. However, note that [HMAC] strongly discourages a key length less than the output length. Nonetheless, we describe handling of shorter lengths here in recognition of shorter lengths typically chosen for IKE or IKEv2 pre-shared keys.
- o If the key is longer than the block size, shorten it by computing the corresponding hash algorithm output over the entire key value, and treat the resulting output value as your HMAC key. Note that this will always result in a key that is less than the block size in length, and this key value will therefore require zero-padding (as described above) prior to use.

2.1.3. Randomness and Key Strength

[HMAC] discusses requirements for key material, including a requirement for strong randomness. Therefore, a strong pseudo-random function MUST be used to generate the required key for use with HMAC-SHA-256+. At the time of this writing there are no published weak keys for use with any HMAC-SHA-256+ algorithms.

2.1.4. Key Distribution

[ARCH] describes the general mechanism for obtaining keying material when multiple keys are required for a single SA (e.g., when an ESP SA requires a key for confidentiality and a key for authentication). In order to provide data origin authentication and integrity verification, the key distribution mechanism must ensure that unique keys are allocated and that they are distributed only to the parties participating in the communication.

2.1.5. Refreshing Keys

Currently, there are no practical attacks against the algorithms recommended here, and especially against the key sizes recommended here. However, as noted in [HMAC] "...periodic key refreshment is a fundamental security practice that helps against potential weaknesses of the function and keys, and limits the damage of an exposed key".

Putting this into perspective, this specification requires 256, 384, or 512-bit keys produced by a strong PRF for use as a MAC. A brute force attack on such keys would take longer to mount than the universe has been in existence. On the other hand, weak keys (e.g., dictionary words) would be dramatically less resistant to attack. It is important to take these points, along with the specific threat model for your particular application and the current state of the art with respect to attacks on SHA-256, SHA-384, and SHA-512 into account when determining an appropriate upper bound for HMAC key lifetimes.

2.2. Padding

The HMAC-SHA-256 algorithms operate on 512-bit blocks of data, while the HMAC-SHA-384 and HMAC-SHA-512 algorithms operate on 1024-bit blocks of data. Padding requirements are specified in [SHA2-1] as part of the underlying SHA-256, SHA-384, and SHA-512 algorithms, so if you implement according to [SHA2-1], you do not need to add any additional padding as far as the HMAC-SHA-256+ algorithms specified here are concerned. With regard to "implicit packet padding" as defined in [AH], no implicit packet padding is required.

2.3. Truncation

The HMAC-SHA-256+ algorithms each produce an nnn-bit value, where nnn corresponds to the output bit length of the algorithm, e.g., HMAC-SHA-nnn. For use as an authenticator, this nnn-bit value can be truncated as described in [HMAC]. When used as a data origin authentication and integrity verification algorithm in ESP, AH, IKE, or IKEv2, a truncated value using the first nnn/2 bits -- exactly half the algorithm output size -- MUST be supported. No other authenticator value lengths are supported by this specification.

Upon sending, the truncated value is stored within the authenticator field. Upon receipt, the entire nnn-bit value is computed and the first nnn/2 bits are compared to the value stored in the authenticator field, with the value of 'nnn' depending on the negotiated algorithm.

[HMAC] discusses potential security benefits resulting from truncation of the output MAC value, and in general, encourages HMAC users to perform MAC truncation. In the context of IPsec, a truncation length of nnn/2 bits is selected because it corresponds to the birthday attack bound for each of the HMAC-SHA-256+ algorithms, and it simultaneously serves to minimize the additional bits on the wire resulting from use of this facility.

2.4. Using HMAC-SHA-256+ as PRFs in IKE and IKEv2

The PRF-HMAC-SHA-256 algorithm is identical to HMAC-SHA-256-128, except that variable-length keys are permitted, and the truncation step is NOT performed. Likewise, the implementations of PRF-HMAC-SHA-384 and PRF-HMAC-SHA-512 are identical to those of HMAC-SHA-384-192 and HMAC-SHA-512-256 respectively, except that again, variable-length keys are permitted, and truncation is NOT performed.

2.5. Interactions with the ESP, IKE, or IKEv2 Cipher Mechanisms

As of this writing, there are no known issues that preclude the use of the HMAC-SHA-256+ algorithms with any specific cipher algorithm.

2.6. HMAC-SHA-256+ Parameter Summary

The following table serves to summarize the various quantities associated with the HMAC-SHA-256+ algorithms. In this table, "var" stands for "variable".

| Algorithm ID | Block Size | Output Length | Trunc. Length | Key Length | Algorithm Type |
|------------------|---------------|------------------|------------------|---------------|-------------------|
| HMAC-SHA-256-128 | 512 | 256 | 128 | 256 | auth/integ |
| HMAC-SHA-384-192 | 1024 | 384 | 192 | 384 | auth/integ |
| HMAC-SHA-512-256 | 1024 | 512 | 256 | 512 | auth/integ |
| PRF-HMAC-SHA-256 | 512 | 256 | (none) | var | PRF |
| PRF-HMAC-SHA-384 | 1024 | 384 | (none) | var | PRF |
| PRF-HMAC-SHA-512 | 1024 | 512 | (none) | var | PRF |

2.7. Test Vectors

The following test cases include the key, the data, and the resulting authenticator, and/or PRF values for each algorithm. The values of keys and data are either ASCII character strings (surrounded by double quotes) or hexadecimal numbers. If a value is an ASCII character string, then the HMAC computation for the corresponding test case DOES NOT include the trailing null character ('\0') of the string. The computed HMAC values are all hexadecimal numbers.

Test Case PRF-5:

```
Key =      aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaa                                     (131 bytes)

Data =      54657374205573696e67204c61726765  ("Test Using Large")
           72205468616e20426c6f636b2d53697a  ("r Than Block-Siz")
           65204b6579202d2048617368204b6579  ("e Key - Hash Key")
           204669727374                        (" First")

PRF-HMAC-SHA-256 = 60e431591ee0b67f0d8a26aacbf5b77f
                  8e0bc6213728c5140546040f0ee37f54

PRF-HMAC-SHA-384 = 4ece084485813e9088d2c63a041bc5b4
                  4f9ef1012a2b588f3cd11f05033ac4c6
                  0c2ef6ab4030fe8296248df163f44952

PRF-HMAC-SHA-512 = 80b24263c7c1a3ebb71493c1dd7be8b4
                  9b46d1f41b4aeec1121b013783f8f352
                  6b56d037e05f2598bd0fd2215d6a1e52
                  95e64f73f63f0aec8b915a985d786598
```

Test Case PRF-6:

```

Key =      aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
           aaaaaa                                     (131 bytes)

Data =      54686973206973206120746573742075  ("This is a test u")
           73696e672061206c6172676572207468  ("sing a larger th")
           616e20626c6f636b2d73697a65206b65  ("an block-size ke")
           7920616e642061206c61726765722074  ("y and a larger t")
           68616e20626c6f636b2d73697a652064  ("han block-size d")
           6174612e20546865206b6579206e6565  ("ata. The key nee")
           647320746f2062652068617368656420  ("ds to be hashed ")
           6265666f7265206265696e6720757365  ("before being use")
           642062792074686520484d414320616c  ("d by the HMAC al")
           676f726974686d2e                    ("gorithm.")

PRF-HMAC-SHA-256 = 9b09ffa71b942fcb27635fbcd5b0e944
                  bfdc63644f0713938a7f51535c3a35e2

PRF-HMAC-SHA-384 = 6617178e941f020d351e2f254e8fd32c
                  602420feb0b8fb9adccebb82461e99c5
                  a678cc31e799176d3860e6110c46523e

PRF-HMAC-SHA-512 = e37b6a775dc87dbaa4dfa9f96e5e3ffd
                  debd71f8867289865df5a32d20cdc944
                  b6022cac3c4982b10d5eeb55c3e4de15
                  134676fb6de0446065c97440fa8c6a58

```

2.7.2. Authenticator Test Vectors

The following sections are test cases for HMAC-SHA256-128, HMAC-SHA384-192, and HMAC-SHA512-256. PRF outputs are also included for convenience. These test cases were generated using the SHA256+ reference code provided in [SHA256+].

2.7.2.1. SHA256 Authentication Test Vectors

Test Case AUTH256-1:

```
Key =      0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b  
          0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b    (32 bytes)
```

```
Data = 4869205468657265 ("Hi There")
```

```
PRF-HMAC-SHA-256 = 198a607eb44bfbc69903a0f1cf2bbdc5
                    ba0aa3f3d9ae3c1c7a3b1696a0b68cf7
```

HMAC-SHA-256-128 = 198a607eb44bfbcb69903a0f1cf2bbdc5

Test Case AUTH256-2:

```
Key = 4a6566654a6566654a6566654a656665 ("JefeJefeJefeJefe")
      4a6566654a6566654a6566654a656665 ("JefeJefeJefeJefe")
```

```
Data = 7768617420646f20796120777616e7420 ("what do ya want ")
        666f72206e6f7468696e673f          ("for nothing?")
```

```
PRF-HMAC-SHA-256 = 167f928588c5cc2eef8e3093caa0e87c
                    9ff566a14794aa61648d81621a2a40c6
```

HMAC-SHA-256-128 = 167f928588c5cc2eef8e3093caa0e87c

Test Case AUTH256-3:

```
Key = aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
      aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa (32 bytes)
```

```
Data =      ddddddddddddddddddddddddddddddddddd
            ddddddddddddddddddddddddddddddddddd
            ddddddddddddddddddddddddddddddddddd
            dddd                                     (50 bytes)
```

```
PRF-HMAC-SHA-256 = cdcbl220d1ecccea91e53aba3092f962
                    e549fe6ce9ed7fdc43191fbde45c30b0
```

HMAC-SHA-256-128 = cdcbl220d1ecccea91e53aba3092f962

HMAC-SHA-256-128 = 372efcf9b40b35c2115b1346903d2ef4

2.7.2.2. SHA384 Authentication Test Vectors

HMAC-SHA-384-128 = b6a8d5636f5c6a7224f9977dcf7ee6c7
fb6d0c48cbdee973

HMAC-SHA-384-192 = 2c7353974f1842fd66d53c452ca42122
b28c0b594cfb184d

Test Case AUTH384-3:

Key = aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa (48 bytes)

Data = dddddddddddddddddddddddddddddddddddd
ddddddddddddddddddddddddddddddddddd
ddddddddddddddddddddddddddddddddddd
dddd (50 bytes)

PRF-HMAC-SHA-384 = 809f439be00274321d4a538652164b53
554a508184a0c3160353e3428597003d
35914a18770f9443987054944b7c4b4a

HMAC-SHA-384-192 = 809f439be00274321d4a538652164b53
554a508184a0c316

Test Case AUTH384-4:

Key = 0102030405060708090a0b0c0d0e0f10
1112131415161718191a1b1c1d1e1f20
0a0b0c0d0e0f10111213141516171819 (48 bytes)

Data = cdcddcdcdcdcdcdcdcdcdcdcdcdcdcdcdcd
cdcdcdcdcdcdcdcdcdcdcdcdcdcdcdcdcd
cdcdcdcdcdcdcdcdcdcdcdcdcdcdcdcdcd
cdcd (50 bytes)

PRF-HMAC-SHA-384 = 5b540085c6e6358096532b2493609ed1
cb298f774f87bb5c2ebf182c83cc7428
707fb92eab2536a5812258228bc96687

HMAC-SHA-384-192 = 5b540085c6e6358096532b2493609ed1
cb298f774f87bb5c

Test Case AUTH512-3:

Key = aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa
aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa (64 bytes)

Data = dddddddddddddddddddddddddddddddd
dddddddddddddddddddddddddddddddd
dddddddddddddddddddddddddddddddd
dddd (50 bytes)

PRF-HMAC-SHA-512 = 2ee7acd783624ca9398710f3ee05ae41
b9f9b0510c87e49e586cc9bf961733d8
623c7b55cebefccf02d5581acc1c9d5f
b1ff68alde45509fbe4da9a433922655

HMAC-SHA-512-256 = 2ee7acd783624ca9398710f3ee05ae41
b9f9b0510c87e49e586cc9bf961733d8

Test Case AUTH512-4:

Key = 0a0b0c0d0e0f10111213141516171819
0102030405060708090a0b0c0d0e0f10
1112131415161718191a1b1c1d1e1f20
2122232425262728292a2b2c2d2e2f30
3132333435363738393a3b3c3d3e3f40 (64 bytes)

Data = cdcdcdcdcdcdcdcdcdcdcdcdcdcdcdcd
cdcdcdcdcdcdcdcdcdcdcdcdcdcdcdcd
cdcdcdcdcdcdcdcdcdcdcdcdcdcdcdcd
cdcd (50 bytes)

PRF-HMAC-SHA-512 = 5e6688e5a3daec826ca32eaea224eff5
e700628947470e13ad01302561bab108
b8c48cbc6b807dcfbd850521a685bab
c7eae4a2a2e660dc0e86b931d65503fd2

HMAC-SHA-512-256 = 5e6688e5a3daec826ca32eaea224eff5
e700628947470e13ad01302561bab108

3. Security Considerations

In a general sense, the security provided by the HMAC-SHA-256+ algorithms is based both upon the strength of the underlying hash algorithm, and upon the additional strength derived from the HMAC construct. At the time of this writing, there are no practical cryptographic attacks against SHA-256, SHA-384, SHA-512, or HMAC. However, as with any cryptographic algorithm, an important component of these algorithms' strength lies in the correctness of the algorithm implementation, the security of the key management mechanism, the strength of the associated secret key, and upon the correctness of the implementation in all of the participating systems. This specification contains test vectors to assist in verifying the correctness of the algorithm implementation, but these in no way verify the correctness (or security) of the surrounding security infrastructure.

3.1. HMAC Key Length vs Truncation Length

There are important differences between the security levels afforded by HMAC-SHA1-96 [HMAC-SHA1] and the HMAC-SHA-256+ algorithms, but there are also considerations that are somewhat counter-intuitive. There are two different axes along which we gauge the security of these algorithms: HMAC output length and HMAC key length. If we assume the HMAC key is a well-guarded secret that can only be determined through offline attacks on observed values, and that its length is less than or equal to the output length of the underlying hash algorithm, then the key's strength is directly proportional to its length. And if we assume an adversary has no knowledge of the HMAC key, then the probability of guessing a correct MAC value for any given packet is directly proportional to the HMAC output length.

This specification defines truncation to output lengths of either 128, 192, or 256 bits. It is important to note that at this time, it is not clear that HMAC-SHA-256 with a truncation length of 128 bits is any more secure than HMAC-SHA1 with the same truncation length, assuming the adversary has no knowledge of the HMAC key. This is because in such cases, the adversary must predict only those bits that remain after truncation. Since in both cases that output length is the same (128 bits), the adversary's odds of correctly guessing the value are also the same in either case: 1 in 2^{128} . Again, if we assume the HMAC key remains unknown to the attacker, then only a bias in one of the algorithms would distinguish one from the other. Currently, no such bias is known to exist in either HMAC-SHA1 or HMAC-SHA-256+.

If, on the other hand, the attacker is focused on guessing the HMAC key, and we assume that the hash algorithms are indistinguishable

when viewed as PRF's, then the HMAC key length provides a direct measure of the underlying security: the longer the key, the harder it is to guess. This means that with respect to passive attacks on the HMAC key, size matters - and the HMAC-SHA-256+ algorithms provide more security in this regard than HMAC-SHA1-96.

4. IANA Considerations

This document does not specify the conventions for using SHA256+ for IKE Phase 1 negotiations, except to note that IANA has made the following IKE hash algorithm attribute assignments:

SHA2-256: 4

SHA2-384: 5

SHA2-512: 6

For IKE Phase 2 negotiations, IANA has assigned the following authentication algorithm identifiers:

HMAC-SHA2-256: 5

HMAC-SHA2-384: 6

HMAC-SHA2-512: 7

For use of HMAC-SHA-256+ as a PRF in IKEv2, IANA has assigned the following IKEv2 Pseudo-random function (type 2) transform identifiers:

PRF_HMAC_SHA2_256 5

PRF_HMAC_SHA2_384 6

PRF_HMAC_SHA2_512 7

For the use of HMAC-SHA-256+ algorithms for data origin authentication and integrity verification in IKEv2, ESP, or AH, IANA has assigned the following IKEv2 integrity (type 3) transform identifiers:

AUTH_HMAC_SHA2_256_128 12

AUTH_HMAC_SHA2_384_192 13

AUTH_HMAC_SHA2_512_256 14

5. Acknowledgements

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6. References

6.1. Normative References

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6.2. Informative References

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