HMAC: Keyed-Hashing for Message Authentication

Status of This Memo

Abstract

   This document describes HMAC, a mechanism for message authentication
   using cryptographic hash functions. HMAC can be used with any
   iterative cryptographic hash function, e.g., MD5, SHA-1, in
   combination with a secret shared key. The cryptographic strength of
   HMAC depends on the properties of the underlying hash function.

1. Introduction

   Providing a way to check the integrity of information transmitted
   over or stored in an unreliable medium is a prime necessity in the
   world of open computing and communications. Mechanisms that provide
   such integrity check based on a secret key are usually called
   "message authentication codes" (MAC). Typically, message
   authentication codes are used between two parties that share a secret
   key in order to validate information transmitted between these
   parties. In this document we present such a MAC mechanism based on
   cryptographic hash functions. This mechanism, called HMAC, is based
   on work by the authors [BCK1] where the construction is presented and
   cryptographically analyzed. We refer to that work for the details on
   the rationale and security analysis of HMAC, and its comparison to
   other keyed-hash methods.

HMAC can be used in combination with any iterated cryptographic hash
function. MD5 and SHA-1 are examples of such hash functions. HMAC
also uses a secret key for calculation and verification of the
message authentication values. The main goals behind this
construction are

* To use, without modifications, available hash functions.
  In particular, hash functions that perform well in software,
  and for which code is freely and widely available.

* To preserve the original performance of the hash function without
  incurring a significant degradation.

* To use and handle keys in a simple way.

* To have a well understood cryptographic analysis of the strength of
  the authentication mechanism based on reasonable assumptions on the
  underlying hash function.

* To allow for easy replaceability of the underlying hash function in
  case that faster or more secure hash functions are found or
  required.

This document specifies HMAC using a generic cryptographic hash
function (denoted by H). Specific instantiations of HMAC need to
define a particular hash function. Current candidates for such hash
functions include SHA-1 [SHA], MD5 [MD5], RIPEMD-128/160 [RIPEMD].
These different realizations of HMAC will be denoted by HMAC-SHA1,
HMAC-MD5, HMAC-RIPEMD, etc.

Note: To the date of writing of this document MD5 and SHA-1 are the
most widely used cryptographic hash functions. MD5 has been recently
shown to be vulnerable to collision search attacks [Dobb]. This
attack and other currently known weaknesses of MD5 do not compromise
the use of MD5 within HMAC as specified in this document (see
[Dobb]); however, SHA-1 appears to be a cryptographically stronger
function. To this date, MD5 can be considered for use in HMAC for
applications where the superior performance of MD5 is critical.   In
any case, implementers and users need to be aware of possible
cryptanalytic developments regarding any of these cryptographic hash
functions, and the eventual need to replace the underlying hash
function. (See section 6 for more information on the security of
HMAC.)

2. Definition of HMAC

   The definition of HMAC requires a cryptographic hash function, which
   we denote by H, and a secret key K. We assume H to be a cryptographic
   hash function where data is hashed by iterating a basic compression
   function on blocks of data.   We denote by B the byte-length of such
   blocks (B=64 for all the above mentioned examples of hash functions),
   and by L the byte-length of hash outputs (L=16 for MD5, L=20 for
   SHA-1).   The authentication key K can be of any length up to B, the
   block length of the hash function. Applications that use keys longer
   than B bytes will first hash the key using H and then use the
   resultant L byte string as the actual key to HMAC. In any case the
   minimal recommended length for K is L bytes (as the hash output
   length). See section 3 for more information on keys.

   We define two fixed and different strings ipad and opad as follows
   (the 'i' and 'o' are mnemonics for inner and outer):

                    ipad = the byte 0x36 repeated B times
                    opad = the byte 0x5C repeated B times.

   To compute HMAC over the data 'text' we perform

                    H(K XOR opad, H(K XOR ipad, text))

   Namely,

     (1) append zeros to the end of K to create a B byte string
         (e.g., if K is of length 20 bytes and B=64, then K will be
          appended with 44 zero bytes 0x00)
     (2) XOR (bitwise exclusive-OR) the B byte string computed in step
         (1) with ipad
     (3) append the stream of data 'text' to the B byte string resulting
         from step (2)
     (4) apply H to the stream generated in step (3)
     (5) XOR (bitwise exclusive-OR) the B byte string computed in
         step (1) with opad
     (6) append the H result from step (4) to the B byte string
         resulting from step (5)
     (7) apply H to the stream generated in step (6) and output
         the result

   For illustration purposes, sample code based on MD5 is provided as an
   appendix.

3. Keys

   The key for HMAC can be of any length (keys longer than B bytes are
   first hashed using H). However, less than L bytes is strongly
   discouraged as it would decrease the security strength of the
   function. Keys longer than L bytes are acceptable but the extra
   length would not significantly increase the function strength. (A
   longer key may be advisable if the randomness of the key is
   considered weak.)

   Keys need to be chosen at random (or using a cryptographically strong
   pseudo-random generator seeded with a random seed), and periodically
   refreshed. (Current attacks do not indicate a specific recommended
   frequency for key changes as these attacks are practically
   infeasible. However, 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.)

4. Implementation Note

   HMAC is defined in such a way that the underlying hash function H can
   be used with no modification to its code. In particular, it uses the
   function H with the pre-defined initial value IV (a fixed value
   specified by each iterative hash function to initialize its
   compression function). However, if desired, a performance
   improvement can be achieved at the cost of (possibly) modifying the
   code of H to support variable IVs.

   The idea is that the intermediate results of the compression function
   on the B-byte blocks (K XOR ipad) and (K XOR opad) can be precomputed
   only once at the time of generation of the key K, or before its first
   use. These intermediate results are stored and then used to
   initialize the IV of H each time that a message needs to be
   authenticated. This method saves, for each authenticated message,
   the application of the compression function of H on two B-byte blocks
   (i.e., on (K XOR ipad) and (K XOR opad)). Such a savings may be
   significant when authenticating short streams of data. We stress
   that the stored intermediate values need to be treated and protected
   the same as secret keys.

   Choosing to implement HMAC in the above way is a decision of the
   local implementation and has no effect on inter-operability.

5. Truncated output

   A well-known practice with message authentication codes is to
   truncate the output of the MAC and output only part of the bits
   (e.g., [MM, ANSI]). Preneel and van Oorschot [PV] show some
   analytical advantages of truncating the output of hash-based MAC
   functions. The results in this area are not absolute as for the
   overall security advantages of truncation. It has advantages (less
   information on the hash result available to an attacker) and
   disadvantages (less bits to predict for the attacker). Applications
   of HMAC can choose to truncate the output of HMAC by outputting the t
   leftmost bits of the HMAC computation for some parameter t (namely,
   the computation is carried in the normal way as defined in section 2
   above but the end result is truncated to t bits). We recommend that
   the output length t be not less than half the length of the hash
   output (to match the birthday attack bound) and not less than 80 bits
   (a suitable lower bound on the number of bits that need to be
   predicted by an attacker). We propose denoting a realization of HMAC
   that uses a hash function H with t bits of output as HMAC-H-t. For
   example, HMAC-SHA1-80 denotes HMAC computed using the SHA-1 function
   and with the output truncated to 80 bits. (If the parameter t is not
   specified, e.g. HMAC-MD5, then it is assumed that all the bits of the
   hash are output.)

6. Security

   The security of the message authentication mechanism presented here
   depends on cryptographic properties of the hash function H: the
   resistance to collision finding (limited to the case where the
   initial value is secret and random, and where the output of the
   function is not explicitly available to the attacker), and the
   message authentication property of the compression function of H when
   applied to single blocks (in HMAC these blocks are partially unknown
   to an attacker as they contain the result of the inner H computation
   and, in particular, cannot be fully chosen by the attacker).

   These properties, and actually stronger ones, are commonly assumed
   for hash functions of the kind used with HMAC. In particular, a hash
   function for which the above properties do not hold would become
   unsuitable for most (probably, all) cryptographic applications,
   including alternative message authentication schemes based on such
   functions. (For a complete analysis and rationale of the HMAC
   function the reader is referred to [BCK1].)

Given the limited confidence gained so far as for the cryptographic
strength of candidate hash functions, it is important to observe the
following two properties of the HMAC construction and its secure use
for message authentication:

1. The construction is independent of the details of the particular
hash function H in use and then the latter can be replaced by any
other secure (iterative) cryptographic hash function.

2. Message authentication, as opposed to encryption, has a
"transient" effect. A published breaking of a message authentication
scheme would lead to the replacement of that scheme, but would have
no adversarial effect on information authenticated in the past. This
is in sharp contrast with encryption, where information encrypted
today may suffer from exposure in the future if, and when, the
encryption algorithm is broken.

The strongest attack known against HMAC is based on the frequency of
collisions for the hash function H ("birthday attack") [PV,BCK2], and
is totally impractical for minimally reasonable hash functions.

As an example, if we consider a hash function like MD5 where the
output length equals L=16 bytes (128 bits) the attacker needs to
acquire the correct message authentication tags computed (with the
same secret key K!) on about 2**64 known plaintexts. This would
require the processing of at least 2**64 blocks under H, an
impossible task in any realistic scenario (for a block length of 64
bytes this would take 250,000 years in a continuous 1Gbps link, and
without changing the secret key K during all this time). This attack
could become realistic only if serious flaws in the collision
behavior of the function H are discovered (e.g. collisions found
after 2**30 messages). Such a discovery would determine the immediate
replacement of the function H (the effects of such failure would be
far more severe for the traditional uses of H in the context of
digital signatures, public key certificates, etc.).

Note: this attack needs to be strongly contrasted with regular
collision attacks on cryptographic hash functions where no secret key
is involved and where 2**64 off-line parallelizable (!) operations
suffice to find collisions. The latter attack is approaching
feasibility [VW] while the birthday attack on HMAC is totally
impractical. (In the above examples, if one uses a hash function
with, say, 160 bit of output then 2**64 should be replaced by 2**80.)

A correct implementation of the above construction, the choice of
random (or cryptographically pseudorandom) keys, a secure key
exchange mechanism, frequent key refreshments, and good secrecy
protection of keys are all essential ingredients for the security of
the integrity verification mechanism provided by HMAC.

Appendix -- Sample Code

    For the sake of illustration we provide the following sample code for
    the implementation of HMAC-MD5 as well as some corresponding test
    vectors (the code is based on MD5 code as described in [MD5]).

```
/*
** Function: hmac_md5
*/

void
hmac_md5(text, text_len, key, key_len, digest)
unsigned char*  text;                /* pointer to data stream */
int             text_len;            /* length of data stream */
unsigned char*  key;                 /* pointer to authentication key */
int             key_len;             /* length of authentication key */
caddr_t         digest;              /* caller digest to be filled in */

{
        MD5_CTX context;
        unsigned char k_ipad[65];    /* inner padding -
                                      * key XORd with ipad
                                      */
        unsigned char k_opad[65];    /* outer padding -
                                      * key XORd with opad
                                      */
        unsigned char tk[16];
        int i;
        /* if key is longer than 64 bytes reset it to key=MD5(key) */
        if (key_len > 64) {

                MD5_CTX      tctx;

                MD5Init(&tctx);
                MD5Update(&tctx, key, key_len);
                MD5Final(tk, &tctx);

                key = tk;
                key_len = 16;
        }

        /*
         * the HMAC_MD5 transform looks like:
         *
         * MD5(K XOR opad, MD5(K XOR ipad, text))
         *
         * where K is an n byte key
         * ipad is the byte 0x36 repeated 64 times
```

```
        * opad is the byte 0x5c repeated 64 times
        * and text is the data being protected
        */

       /* start out by storing key in pads */
       bzero( k_ipad, sizeof k_ipad);
       bzero( k_opad, sizeof k_opad);
       bcopy( key, k_ipad, key_len);
       bcopy( key, k_opad, key_len);

       /* XOR key with ipad and opad values */
       for (i=0; i<64; i++) {
               k_ipad[i] ^= 0x36;
               k_opad[i] ^= 0x5c;
       }
       /*
        * perform inner MD5
        */
       MD5Init(&context);                     /* init context for 1st
                                               * pass */
       MD5Update(&context, k_ipad, 64)     /* start with inner pad */
       MD5Update(&context, text, text_len); /* then text of datagram */
       MD5Final(digest, &context);         /* finish up 1st pass */
       /*
        * perform outer MD5
        */
       MD5Init(&context);                     /* init context for 2nd
                                               * pass */
       MD5Update(&context, k_opad, 64);    /* start with outer pad */
       MD5Update(&context, digest, 16);    /* then results of 1st
                                            * hash */
       MD5Final(digest, &context);         /* finish up 2nd pass */
}
```

Test Vectors (Trailing '\0' of a character string not included in test):

```
  key =         0x0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b0b
  key_len =     16 bytes
  data =        "Hi There"
  data_len =    8  bytes
  digest =      0x9294727a3638bb1c13f48ef8158bfc9d

  key =         "Jefe"
  data =        "what do ya want for nothing?"
  data_len =    28 bytes
  digest =      0x750c783e6ab0b503eaa86e310a5db738

  key =         0xAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

```
   key_len         16 bytes
   data =          0xDDDDDDDDDDDDDDDDDDDD...
                   ..DDDDDDDDDDDDDDDDDDDD...
                   ..DDDDDDDDDDDDDDDDDDDD...
                   ..DDDDDDDDDDDDDDDDDDDD...
                   ..DDDDDDDDDDDDDDDDDDDD
   data_len =      50 bytes
   digest =        0x56be34521d144c88dbb8c733f0e8b3f6
```

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References

   [ANSI] ANSI X9.9, "American National Standard for Financial
           Institution Message Authentication (Wholesale)," American
           Bankers Association, 1981.   Revised 1986.

   [Atk]   Atkinson, R., "IP Authentication Header", RFC 1826, August
           1995.

   [BCK1] M. Bellare, R. Canetti, and H. Krawczyk,
           "Keyed Hash Functions and Message Authentication",
           Proceedings of Crypto'96, LNCS 1109, pp. 1-15.
           (http://www.research.ibm.com/security/keyed-md5.html)

   [BCK2] M. Bellare, R. Canetti, and H. Krawczyk,
           "Pseudorandom Functions Revisited: The Cascade Construction",
           Proceedings of FOCS'96.

   [Dobb] H. Dobbertin, "The Status of MD5 After a Recent Attack",
           RSA Labs' CryptoBytes, Vol. 2 No. 2, Summer 1996.
           http://www.rsa.com/rsalabs/pubs/cryptobytes.html

   [PV]   B. Preneel and P. van Oorschot, "Building fast MACs from hash
           functions", Advances in Cryptology -- CRYPTO'95 Proceedings,
           Lecture Notes in Computer Science, Springer-Verlag Vol.963,
           1995, pp. 1-14.

   [MD5]   Rivest, R., "The MD5 Message-Digest Algorithm",
           RFC 1321, April 1992.

   [MM]   Meyer, S. and Matyas, S.M., Cryptography, New York Wiley,
            1982.

   [RIPEMD] H. Dobbertin, A. Bosselaers, and B. Preneel, "RIPEMD-160: A
             strengthened version of RIPEMD", Fast Software Encryption,
             LNCS Vol 1039, pp. 71-82.
              ftp://ftp.esat.kuleuven.ac.be/pub/COSIC/bosselae/ripemd/.

   [SHA]   NIST, FIPS PUB 180-1: Secure Hash Standard, April 1995.

   [Tsu]   G. Tsudik, "Message authentication with one-way hash
            functions", In Proceedings of Infocom'92, May 1992.
            (Also in "Access Control and Policy Enforcement in
             Internetworks", Ph.D. Dissertation, Computer Science
             Department, University of Southern California, April 1991.)

   [VW]   P. van Oorschot and M. Wiener, "Parallel Collision
            Search with Applications to Hash Functions and Discrete
            Logarithms", Proceedings of the 2nd ACM Conf. Computer and
            Communications Security, Fairfax, VA, November 1994.

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