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Hash-Based Signatures
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Abstract

This note describes a digital signature system based on cryptographic hash functions, following the seminal work in this area of Lamport, Diffie, Winternitz, and Merkle, as adapted by Leighton and Micali in 1995. It specifies a one-time signature scheme and a general signature scheme. These systems provide asymmetric authentication without using large integer mathematics and can achieve a high security level. They are suitable for compact implementations, are relatively simple to implement, and naturally resist side-channel attacks. Unlike most other signature systems, hash-based signatures would still be secure even if it proves feasible for an attacker to build a quantum computer.

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Table of Contents

1.	Introduction	3
1.1.	Conventions Used In This Document	4
2.	Interface	5
3.	Notation	5
3.1.	Data Types	5
3.1.1.	Operators	6
3.1.2.	Functions	6
3.1.3.	Strings of w-bit elements	7
3.2.	Typecodes	8
4.	LM-OTS One-Time Signatures	8
4.1.	Parameters	8
4.2.	Private Key	9
4.3.	Public Key	10
4.4.	Checksum	11
4.5.	Signature Generation	12
4.6.	Signature Verification	13
5.	Leighton-Micali Signatures	14
5.1.	Parameters	15
5.2.	LMS Private Key	15
5.3.	LMS Public Key	16
5.4.	LMS Signature	17
5.4.1.	LMS Signature Generation	18
5.4.2.	LMS Signature Verification	19
6.	Hierarchical signatures	21
6.1.	Key Generation	22
6.2.	Signature Generation	23
6.3.	Signature Verification	25
7.	Formats	25
8.	Rationale	28
8.1.	Security string	29
9.	History	30
10.	IANA Considerations	32
11.	Intellectual Property	34

11.1.	Disclaimer	34
12.	Security Considerations	34
12.1.	Hash Formats	35
12.2.	Stateful signature algorithm	36
12.3.	Security of LM-OTS Checksum	37

13.	Comparison with other work	38
14.	Acknowledgements	38
15.	References	38
15.1.	Normative References	38
15.2.	Informative References	39
Appendix A.	Pseudorandom Key Generation	40
Appendix B.	LM-OTS Parameter Options	41
Appendix C.	An iterative algorithm for computing an LMS public key	42
Appendix D.	Method for deriving authentication path for a signature	43
Appendix E.	Example Implementation	44
Appendix F.	Parameter Set Recommendations	44
Appendix G.	Test Cases	45
	Authors' Addresses	57

[1.](#) Introduction

One-time signature systems, and general purpose signature systems built out of one-time signature systems, have been known since 1979 [[Merkle79](#)], were well studied in the 1990s [[USPT05432852](#)], and have benefited from renewed attention in the last decade. The characteristics of these signature systems are small private and public keys and fast signature generation and verification, but large signatures and moderately slow key generation (in comparison with RSA and ECDSA). Private keys can be made very small by appropriate key generation, for example, as described in [Appendix A](#). In recent years there has been interest in these systems because of their post-quantum security and their suitability for compact verifier implementations.

This note describes the Leighton and Micali adaptation [[USPT05432852](#)] of the original Lamport-Diffie-Winternitz-Merkle one-time signature system [[Merkle79](#)] [[C:Merkle87](#)][[C:Merkle89a](#)][[C:Merkle89b](#)] and general signature system [[Merkle79](#)] with enough specificity to ensure interoperability between implementations.

A signature system provides asymmetric message authentication. The key generation algorithm produces a public/private key pair. A message is signed by a private key, producing a signature, and a message/signature pair can be verified by a public key. A One-Time Signature (OTS) system can be used to sign one message securely, but will become insecure if more than one is signed with the same public/private key pair. An N-time signature system can be used to sign N or fewer messages securely. A Merkle tree signature scheme is an N-time signature system that uses an OTS system as a component.

In the Merkle scheme, a binary tree of height h is used to hold 2^h OTS key pairs. Each interior node of the tree holds a value which is the hash of the values of its two children nodes. The public key of the tree is the value of the root node (a recursive hash of the OTS public keys), while the private key of the tree is the collection of all the OTS private keys, together with the index of the next OTS private key to sign the next message with.

In this note we describe the Leighton-Micali Signature (LMS) system, which is a variant of the Merkle scheme, and a Hierarchical Signature System (HSS) built on top of it that can efficiently scale to larger numbers of signatures. In order to support signing a large number of messages on resource constrained systems, the Merkle tree can be subdivided into a number of smaller trees. Only the bottom-most tree is used to sign messages, while trees above that are used to sign the public keys of their children. For example, in the simplest case with 2 levels with both levels consisting of height h trees, the root tree is used to sign 2^h trees with 2^h OTS key pairs, and each second level tree has 2^h OTS key pairs, for a total of $2^{(2h)}$ bottom level key pairs, and so can sign $2^{(2h)}$ messages. The advantage of this scheme is that only the active trees need to be instantiated, which saves both time (for key generation) and space (for key storage). On the other hand, using a multilevel signature scheme increases the size of the signature, as well as the signature verification time.

This note is structured as follows. Notation is introduced in [Section 3](#). The LM-OTS signature system is described in [Section 4](#), and the LMS and HSS N-time signature systems are described in

[Section 5](#) and [Section 6](#), respectively. Sufficient detail is provided to ensure interoperability. The public formats are described in [Section 7](#). The rationale for design decisions are given in [Section 8](#). The changes made to this document over previous versions is listed in [Section 9](#). The IANA registry for these signature systems is described in [Section 10](#). Intellectual Property issues are discussed in [Section 11](#). Security considerations are presented in [Section 12](#).

[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](#). Interface

The LMS signing algorithm is stateful; it modifies and updates the private key as a side effect of generating a signature. Once a particular value of the private key is used to sign one message, it MUST NOT be used to sign another.

The key generation algorithm takes as input an indication of the parameters for the signature system. If it is successful, it returns both a private key and a public key. Otherwise, it returns an indication of failure.

The signing algorithm takes as input the message to be signed and the current value of the private key. If successful, it returns a signature and the next value of the private key, if there is such a value. After the private key of an N-time signature system has signed N messages, the signing algorithm returns the signature and an indication that there is no next value of the private key that can be used for signing. If unsuccessful, it returns an indication of failure.

The verification algorithm takes as input the public key, a message,

and a signature, and returns an indication of whether or not the signature and message pair is valid.

A message/signature pair is valid if the signature was returned by the signing algorithm upon input of the message and the private key corresponding to the public key; otherwise, the signature and message pair is not valid with probability very close to one.

[3.](#) Notation

[3.1.](#) Data Types

Bytes and byte strings are the fundamental data types. A single byte is denoted as a pair of hexadecimal digits with a leading "0x". A byte string is an ordered sequence of zero or more bytes and is denoted as an ordered sequence of hexadecimal characters with a leading "0x". For example, 0xe534f0 is a byte string with a length of three. An array of byte strings is an ordered set, indexed starting at zero, in which all strings have the same length.

Unsigned integers are converted into byte strings by representing them in network byte order. To make the number of bytes in the representation explicit, we define the functions `u8str(X)`, `u16str(X)`, and `u32str(X)`, which take a non-negative integer `X` as input and return one, two, and four byte strings, respectively. We also make use of the function `strTou32(S)`, which takes a four-byte string `S` as

input and returns a non-negative integer; the identity `u32str(strTou32(S)) = S` holds for any four-byte string `S`.

[3.1.1.](#) Operators

When `a` and `b` are real numbers, mathematical operators are defined as follows:

`^` : `a ^ b` denotes the result of `a` raised to the power of `b`

`*` : `a * b` denotes the product of `a` multiplied by `b`

`/` : `a / b` denotes the quotient of `a` divided by `b`

`%` : `a % b` denotes the remainder of the integer division of `a` by `b`

`+` : `a + b` denotes the sum of `a` and `b`

`-` : `a - b` denotes the difference of `a` and `b`

The standard order of operations is used when evaluating arithmetic expressions.

When `B` is a byte and `i` is an integer, then `B >> i` denotes the logical right-shift operation by `i` positions. Similarly, `B << i` denotes the logical left-shift operation.

If `S` and `T` are byte strings, then `S || T` denotes the concatenation of `S` and `T`. If `S` and `T` are equal length byte strings, then `S AND T` denotes the bitwise logical and operation.

The `i`-th element in an array `A` is denoted as `A[i]`.

[3.1.2.](#) Functions

If `r` is a non-negative real number, then we define the following functions:

`ceil(r)` : returns the smallest integer larger than `r`

`floor(r)` : returns the largest integer smaller than `r`

`lg(r)` : returns the base-2 logarithm of `r`

[3.1.3.](#) Strings of `w`-bit elements

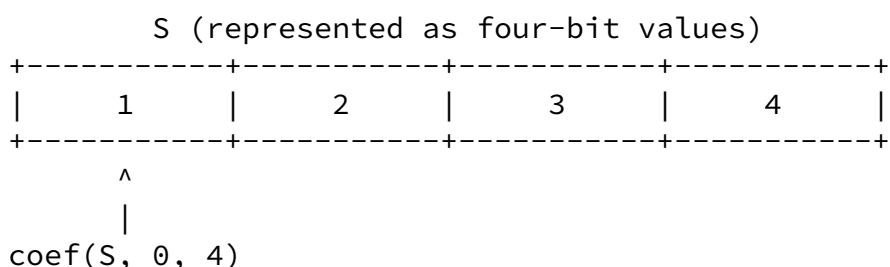
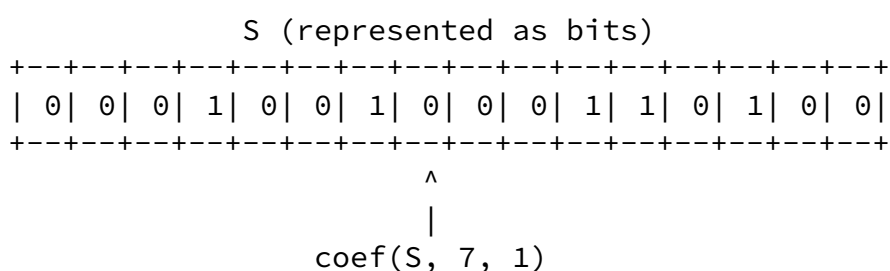
If `S` is a byte string, then `byte(S, i)` denotes its `i`-th byte, where `byte(S, 0)` is the leftmost byte. In addition, `bytes(S, i, j)` denotes the range of bytes from the `i`-th to the `j`-th byte, inclusive. For example, if `S = 0x02040608`, then `byte(S, 0)` is `0x02` and `bytes(S, 1, 2)` is `0x0406`.

A byte string can be considered to be a string of w -bit unsigned integers; the correspondence is defined by the function $\text{coef}(S, i, w)$ as follows:

If S is a string, i is a positive integer, and w is a member of the set $\{1, 2, 4, 8\}$, then $\text{coef}(S, i, w)$ is the i -th, w -bit value, if S is interpreted as a sequence of w -bit values. That is,

$$\text{coef}(S, i, w) = (2^w - 1) \text{ AND } \\ (\text{byte}(S, \text{floor}(i * w / 8)) \gg \\ (8 - (w * (i \% (8 / w)) + w)))$$

For example, if S is the string `0x1234`, then $\text{coef}(S, 7, 1)$ is 0 and $\text{coef}(S, 0, 4)$ is 1.



The return value of coef is an unsigned integer. If i is larger than the number of w -bit values in S , then $\text{coef}(S, i, w)$ is undefined, and an attempt to compute that value should raise an error.

A typecode is an unsigned integer that is associated with a particular data format. The format of the LM-OTS, LMS, and HSS signatures and public keys all begin with a typecode that indicates the precise details used in that format. These typecodes are represented as four-byte unsigned integers in network byte order; equivalently, they are XDR enumerations (see [Section 7](#)).

[4.](#) LM-OTS One-Time Signatures

This section defines LM-OTS signatures. The signature is used to validate the authenticity of a message by associating a secret private key with a shared public key. These are one-time signatures; each private key **MUST** be used at most one time to sign any given message.

As part of the signing process, a digest of the original message is computed using the cryptographic hash function H (see [Section 4.1](#)), and the resulting digest is signed.

In order to facilitate its use in an N-time signature system, the LM-OTS key generation, signing, and verification algorithms all take as input a parameter q , which indicates the leaf of the Merkle tree where the OTS public key appears. This parameter is used as part of the security string, as listed in [Section 8.1](#). When the LM-OTS signature system is used outside of an N-time signature system, this value **SHOULD** be set to the all-zero value.

[4.1.](#) Parameters

The signature system uses the parameters n and w , which are both positive integers. The algorithm description also makes use of the internal parameters p and ls , which are dependent on n and w . These parameters are summarized as follows:

n : the number of bytes of the output of the hash function

w : the width (in bits) of the Winternitz coefficients; it is a member of the set $\{ 1, 2, 4, 8 \}$

p : the number of n -byte string elements that make up the LM-OTS signature

ls : the number of left-shift bits used in the checksum function $Cksm$ (defined in [Section 4.4](#))

H : a second-preimage-resistant cryptographic hash function that accepts byte strings of any length, and returns an n-byte string

For more background on the cryptographic security requirements on H, see the [Section 12](#).

The value of n is determined by the hash function selected for use as part of the LM-OTS algorithm; the choice of this value has a strong effect on the security of the system. The parameter w determines the length of the Winternitz chains computed as a part of the OTS signature (which involve $2^w - 1$ invocations of the hash function); it has little effect on security. Increasing w will shorten the signature, but at a cost of a larger computation to generate and verify a signature. The values of p and ls are dependent on the choices of the parameters n and w, as described in [Appendix B](#). A table illustrating various combinations of n, w, p, and ls is provided in Table 1.

The value of w describes a space/time trade-off; increasing the value of w will cause the signature to shrink (by decreasing the value of p) while increasing the amount of time needed to perform operations with it (generate the public key, generate and verify the signature); in general, the LM-OTS signature is $4 + n \times (p + 1)$ bytes long, and public key generation will take $p \times (2^w - 1) + 1$ hash computations (and signature generation and verification will take about half that on average).

Name	H	n	w	p	ls
LMOTS_SHA256_N32_W1	SHA256	32	1	265	7
LMOTS_SHA256_N32_W2	SHA256	32	2	133	6
LMOTS_SHA256_N32_W4	SHA256	32	4	67	4
LMOTS_SHA256_N32_W8	SHA256	32	8	34	0

Table 1

Here SHA256 denotes the SHA-256 hash function defined in NIST standard [\[FIPS180\]](#).

[4.2](#). Private Key

The format of the LM-OTS private key is an internal matter to the

implementation, and this document does not attempt to define it. One possibility is that the private key may consist of a typecode

indicating the particular LM-OTS algorithm, an array $x[]$ containing p n -byte strings, and the 16-byte string I and the 4 byte string q . This private key MUST be used to sign (at most) one message. The following algorithm shows pseudocode for generating a private key.

Algorithm 0: Generating a Private Key

1. retrieve the values of q and I (the 16-byte identifier of the LMS public/private keypair) from the LMS tree that this key will be used with
2. set $type$ to the typecode of the algorithm
3. set n and p according to the typecode and Table 1
4. compute the array x as follows:
for ($i = 0$; $i < p$; $i = i + 1$) {
 set $x[i]$ to a uniformly random n -byte string
}
}
5. return $u32str(type) || I || u32str(q) || x[0] || x[1] || \dots || x[p-1]$

An implementation MAY use a pseudorandom method to compute $x[i]$, as suggested in [Merkle79], page 46. The details of the pseudorandom method do not affect interoperability, but the cryptographic strength MUST match that of the LM-OTS algorithm. [Appendix A](#) provides an example of a pseudorandom method for computing the LM-OTS private key.

[4.3.](#) Public Key

The LM-OTS public key is generated from the private key by iteratively applying the function H to each individual element of x , for $2^w - 1$ iterations, then hashing all of the resulting values.

The public key is generated from the private key using the following algorithm, or any equivalent process.

Algorithm 1: Generating a One Time Signature Public Key From a Private Key

1. set type to the typecode of the algorithm
2. set the integers n, p, and w according to the typecode and Table 1
3. determine x, I and q from the private key
4. compute the string K as follows:

```
for ( i = 0; i < p; i = i + 1 ) {
    tmp = x[i]
    for ( j = 0; j < 2^w - 1; j = j + 1 ) {
        tmp = H(I || u32str(q) || u16str(i) || u8str(j) || tmp)
    }
    y[i] = tmp
}
K = H(I || u32str(q) || u16str(D_PBLIC) || y[0] || ... || y[p-1])
```
5. return u32str(type) || I || u32str(q) || K

The public key is the value returned by Algorithm 1.

[4.4.](#) Checksum

A checksum is used to ensure that any forgery attempt that manipulates the elements of an existing signature will be detected. This checksum is needed because an attacker can freely advance any of the Winternitz chains. That is, if this checksum were not present, then an attacker who could find a hash that has every digit larger than the valid hash could replace it (and adjust the Winternitz chains). The security property that it provides is detailed in

[Section 12](#). The checksum function Cksm is defined as follows, where S denotes the n-byte string that is input to that function, and the value sum is a 16-bit unsigned integer:

Algorithm 2: Checksum Calculation

```
sum = 0
for ( i = 0; i < (n*8/w); i = i + 1 ) {
    sum = sum + (2^w - 1) - coef(S, i, w)
}
return (sum << ls)
```

Because of the left-shift operation, the rightmost bits of the result of Cksm will often be zeros. Due to the value of p, these bits will not be used during signature generation or verification.

[4.5](#). Signature Generation

The LM-OTS signature of a message is generated by first prepending the LMS key identifier I, the LMS leaf identifier q, the value D_MESG and the randomizer C to the message, then computing the hash, and then concatenating the checksum of the hash to the hash itself, then considering the resulting value as a sequence of w-bit values, and using each of the w-bit values to determine the number of times to apply the function H to the corresponding element of the private key. The outputs of the function H are concatenated together and returned as the signature. The pseudocode for this procedure is shown below.

Algorithm 3: Generating a One Time Signature From a Private Key and a Message

1. set type to the typecode of the algorithm
2. set n, p, and w according to the typecode and Table 1
3. determine x, I and q from the private key
4. set C to a uniformly random n-byte string
5. compute the array y as follows:
Q = H(I || u32str(q) || u16str(D_MESG) || C || message)

```

for ( i = 0; i < p; i = i + 1 ) {
    a = coef(Q || Cksm(Q), i, w)
    tmp = x[i]
    for ( j = 0; j < a; j = j + 1 ) {
        tmp = H(I || u32str(q) || u16str(i) || u8str(j) || tmp)
    }
    y[i] = tmp
}

```

```

6. return u32str(type) || C || y[0] || ... || y[p-1]

```

Note that this algorithm results in a signature whose elements are intermediate values of the elements computed by the public key algorithm in [Section 4.3](#).

The signature is the string returned by Algorithm 3. [Section 7](#) specifies the typecode and more formally defines the encoding and decoding of the string.

[4.6](#). Signature Verification

In order to verify a message with its signature (an array of n-byte strings, denoted as y), the receiver must "complete" the chain of iterations of H using the w-bit coefficients of the string resulting from the concatenation of the message hash and its checksum. This computation should result in a value that matches the provided public key.

Algorithm 4a: Verifying a Signature and Message Using a Public Key

1. if the public key is not at least four bytes long, return INVALID
2. parse pubtype, I, q, and K from the public key as follows:
 - a. pubtype = strTou32(first 4 bytes of public key)
 - b. set n according to the pubkey and Table 1; if the public key is not exactly 24 + n bytes long, return INVALID

- c. I = next 16 bytes of public key
 - d. q = strTou32(next 4 bytes of public key)
 - e. K = next n bytes of public key
3. compute the public key candidate K_c from the signature, message, and the identifiers I and q obtained from the public key, using Algorithm 4b. If Algorithm 4b returns INVALID, then return INVALID.
 4. if K_c is equal to K , return VALID; otherwise, return INVALID

Algorithm 4b: Computing a Public Key Candidate K_c from a Signature, Message, Signature Typecode Type, and identifiers I , q

1. if the signature is not at least four bytes long, return INVALID
2. parse sigtype, C , and y from the signature as follows:
 - a. sigtype = strTou32(first 4 bytes of signature)
 - b. if sigtype is not equal to pubtype, return INVALID
 - c. set n and p according to the pubtype and Table 1; if the

signature is not exactly $4 + n * (p+1)$ bytes long, return INVALID

d. C = next n bytes of signature

e. $y[0]$ = next n bytes of signature

$y[1]$ = next n bytes of signature

...

$y[p-1]$ = next n bytes of signature

3. compute the string K_c as follows

```
Q = H(I || u32str(q) || u16str(D_MESG) || C || message)
```

```
for ( i = 0; i < p; i = i + 1 ) {
```

```
    a = coef(Q || Cksm(Q), i, w)
```

```
    tmp = y[i]
```

```
    for ( j = a; j < 2^w - 1; j = j + 1 ) {
```

```
        tmp = H(I || u32str(q) || u16str(i) || u8str(j) || tmp)
```

```
    }
```

```
    z[i] = tmp
```

```
}
```

```
Kc = H(I || u32str(q) || u16str(D_PBLC) || z[0] || z[1] || ... || z[p-1])
```

4. return K_c

[5. Leighton-Micali Signatures](#)

The Leighton-Micali Signature (LMS) method can sign a potentially large but fixed number of messages. An LMS system uses two cryptographic components: a one-time signature method and a hash function. Each LMS public/private key pair is associated with a perfect binary tree, each node of which contains an m -byte value, where m is the output length of the hash function. Each leaf of the tree contains the value of the public key of an LM-OTS public/private key pair. The value contained by the root of the tree is the LMS public key. Each interior node is computed by applying the hash function to the concatenation of the values of its children nodes.

Each node of the tree is associated with a node number, an unsigned integer that is denoted as `node_num` in the algorithms below, which is computed as follows. The root node has node number 1; for each node with node number $N < 2^h$, its left child has node number $2*N$, while

its right child has node number $2N+1$. The result of this is that each node within the tree will have a unique node number, and the leaves will have node numbers 2^h , $(2^h)+1$, $(2^h)+2$, ..., $(2^h)+(2^h)-1$. In general, the j -th node at level i has node number $2^i + j$. The node number can conveniently be computed when it is needed in the LMS algorithms, as described in those algorithms.

5.1. Parameters

An LMS system has the following parameters:

h : the height of the tree, and

m : the number of bytes associated with each node.

H : a second-preimage-resistant cryptographic hash function that accepts byte strings of any length, and returns an m -byte string.

There are 2^h leaves in the tree. The hash function used within the LMS system SHOULD be the same as the hash function used within the LM-OTS system used to generate the leaves.

Name	H	m	h
LMS_SHA256_M32_H5	SHA256	32	5
LMS_SHA256_M32_H10	SHA256	32	10
LMS_SHA256_M32_H15	SHA256	32	15
LMS_SHA256_M32_H20	SHA256	32	20
LMS_SHA256_M32_H25	SHA256	32	25

Table 2

5.2. LMS Private Key

The format of the LMS private key is an internal matter to the implementation, and this document does not attempt to define it. One possibility is that it may consist of an array `OTS_PRIV[]` of 2^h LM-OTS private keys, and the leaf number q of the next LM-OTS private

key that has not yet been used. The q -th element of `OTS_PRIV[]` is generated using Algorithm 0 with the identifiers I , q . The leaf number q is initialized to zero when the LMS private key is created. The process is as follows:

Algorithm 5: Computing an LMS Private Key.

1. determine h and m from the typecode and Table 2.
2. set I to a uniformly random 16-byte string
3. compute the array `OTS_PRIV[]` as follows:


```
for ( q = 0; q < 2^h; q = q + 1) {
    OTS_PRIV[q] = LM-OTS private key with identifiers I, q
  }
```
4. $q = 0$

An LMS private key MAY be generated pseudorandomly from a secret value, in which case the secret value MUST be at least m bytes long, be uniformly random, and MUST NOT be used for any other purpose than the generation of the LMS private key. The details of how this process is done do not affect interoperability; that is, the public key verification operation is independent of these details. [Appendix A](#) provides an example of a pseudorandom method for computing an LMS private key.

The signature generation logic uses q as the next leaf to use, hence step 3 starts it off at the left-most one.

5.3. LMS Public Key

An LMS public key is defined as follows, where we denote the public key final hash value (namely, the K value computed in algorithm 1) associated with the i -th LM-OTS private key as `OTS_PUB_HASH[i]`, with i ranging from 0 to $(2^h)-1$. Each instance of an LMS public/private key pair is associated with a balanced binary tree, and the nodes of that tree are indexed from 1 to $2^{(h+1)}-1$. Each node is associated with an m -byte string, and the string for the r -th node is denoted as $T[r]$ and is defined as

$$T[r] = \begin{cases} H(I || u32str(r) || u16str(D_LEAF) || OTS_PUB_HASH[r-2^h]) & \text{if } r \geq 2^h, \\ H(I || u32str(r) || u16str(D_INTR) || T[2*r] || T[2*r+1]) & \text{otherwise.} \end{cases}$$

The LMS public key is the string

```
u32str(type) || u32str(otstype) || I || T[1]
```

[Section 7](#) specifies the format of the type variable. The value `otstype` is the parameter set for the LM-OTS public/private keypairs used. The value `I` is the private key identifier, and is the value used for all computations for the same LMS tree. The value `T[1]` can be computed via recursive application of the above equation, or by any equivalent method. An iterative procedure is outlined in [Appendix C](#).

[5.4](#). LMS Signature

An LMS signature consists of

- the number `q` of the leaf associated with the LM-OTS signature, as a four-byte unsigned integer in network byte order,

- an LM-OTS signature,

- a typecode indicating the particular LMS algorithm,

- an array of `h` `m`-byte values that is associated with the path through the tree from the leaf associated with the LM-OTS signature to the root.

Symbolically, the signature can be represented as

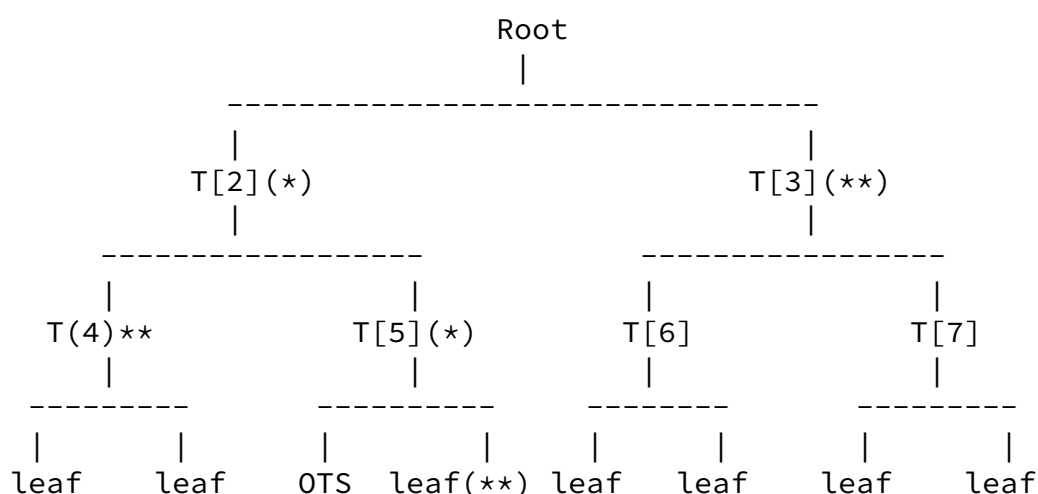
```
u32str(q) || lmots_signature || u32str(type) ||
           path[0] || path[1] || path[2] || ... || path[h-1]
```

[Section 7](#) specifies the typecode and more formally defines the format. The array for a tree with height `h` will have `h` values and contains the values of the siblings of (or adjacent to) the nodes on the path from the leaf to the root, where the sibling to node `A` is the other node which shares node `A`'s parent. In the signature, `0` is counted from the bottom level of the tree, and so `path[0]` is the `b`th value of the node adjacent to leaf node `q`; `path[1]` is the second level node that is adjacent to leaf node `q`'s parent, and so up the tree until we get to `path[h-1]`, which is the value of the next-to-the-top level node that leaf node `q` does not reside in.

Below is a simple example of the authentication path for `h=3` and `q=2`.

The leaf marked OTS is the one time signature which is used to sign the actual message. The nodes on the path from the OTS public key to the root are marked with a (*), while the nodes that are used within the path array are marked with a (**). The values in the path array are those nodes which are siblings of the nodes on the path; path[0] is the leaf(**) node that is adjacent to the OTS public key (which is the start of the path); path[1] is the T[4]** node which is the sibling of the second Node (T[5]*) on the path, and path[2] is the

the T[3]** node which is the sibling of the third Node* (T[2]*) on the path.



The idea behind this authentication path is that it allows us to validate the OTS hash with using the path array values and hash computations. What the verifier does is recompute the hashes up the path; first, he hashes the given OTS and path[0] value, giving a tentative T[5]' value. Then, he hashes his path[1] and tentative T[5]' value to get a tentative T[2]' value. Then, he hashes that and the path[2] value to get a tentative Root' value. If that value is the known public key of the Merkle tree, then we can assume that the value T[2]' he got was the correct T[2] value in the original tree, and so the T[5]' value he got was the correct T[5] value in the original tree, and so the OTS public key is the same as in the original, and hence is correct.

[5.4.1.](#) LMS Signature Generation

To compute the LMS signature of a message with an LMS private key, the signer first computes the LM-OTS signature of the message using the leaf number of the next unused LM-OTS private key. The leaf number q in the signature is set to the leaf number of the LMS private key that was used in the signature. Before releasing the signature, the leaf number q in the LMS private key **MUST** be incremented, to prevent the LM-OTS private key from being used again. If the LMS private key is maintained in nonvolatile memory, then the implementation **MUST** ensure that the incremented value has been stored before releasing the signature. The issue this tries to prevent is a scenario where a) we generate a signature, using one LM-OTS private key, and release it to the application, b) before we update the nonvolatile memory, we crash, and c) we reboot, and generate a second signature using the same LM-OTS private key; with two different

signatures using the same LM-OTS private key, someone could potentially generate a forged signature of a third message.

The array of node values in the signature **MAY** be computed in any way. There are many potential time/storage tradeoffs that can be applied. The fastest alternative is to store all of the nodes of the tree and set the array in the signature by copying them; pseudocode to do so appears in [Appendix D](#). The least storage intensive alternative is to recompute all of the nodes for each signature. Note that the details of this procedure are not important for interoperability; it is not necessary to know any of these details in order to perform the signature verification operation. The internal nodes of the tree need not be kept secret, and thus a node-caching scheme that stores only internal nodes can sidestep the need for strong protections.

Several useful time/storage tradeoffs are described in the 'Small-Memory LM Schemes' section of [\[USPTO5432852\]](#).

[5.4.2](#). LMS Signature Verification

An LMS signature is verified by first using the LM-OTS signature verification algorithm (Algorithm 4b) to compute the LM-OTS public key from the LM-OTS signature and the message. The value of that public key is then assigned to the associated leaf of the LMS tree, then the root of the tree is computed from the leaf value and the array `path[]` as described in Algorithm 6 below. If the root value

matches the public key, then the signature is valid; otherwise, the signature fails.

Algorithm 6: LMS Signature Verification

1. if the public key is not at least eight bytes long, return INVALID
2. parse pubtype, I, and T[1] from the public key as follows:
 - a. pubtype = strTou32(first 4 bytes of public key)
 - b. ots_typecode = strTou32(next 4 bytes of public key)
 - c. set m according to pubtype, based on Table 2
 - d. if the public key is not exactly 24 + m bytes long, return INVALID
 - e. I = next 16 bytes of the public key
 - f. T[1] = next m bytes of the public key

3. compute the LMS Public Key Candidate T_c from the signature, message, identifier, pubkey and ots_typecode using Algorithm 6a.
4. if T_c is equal to $T[1]$, return VALID; otherwise, return INVALID

Algorithm 6a: Computing an LMS Public Key Candidate from a Signature, Message, Identifier, and algorithm typecode

1. if the signature is not at least eight bytes long, return INVALID
2. parse sigtype, q, lmots_signature, and path from the signature as follows:
 - a. $q = \text{strTou32}(\text{first 4 bytes of signature})$
 - b. $\text{otssigtype} = \text{strTou32}(\text{next 4 bytes of signature})$
 - c. if otssigtype is not the OTS typecode from the public key, return INVALID
 - d. set n, p according to otssigtype and Table 1; if the signature is not at least $12 + n * (p + 1)$ bytes long, return INVALID
 - e. $\text{lmots_signature} = \text{bytes 4 through } 8 + n * (p + 1) - 1 \text{ of signature}$
 - f. $\text{sigtype} = \text{strTou32}(4 \text{ bytes of signature at location } 8 + n * (p + 1))$
 - f. if sigtype is not the LM typecode from the public key, return INVALID

- g. set m, h according to sigtype and Table 2
- h. if $q \geq 2^h$ or the signature is not exactly $12 + n * (p + 1) + m * h$ bytes long, return INVALID
- i. set path as follows:
 - $\text{path}[0] = \text{next } m \text{ bytes of signature}$
 - $\text{path}[1] = \text{next } m \text{ bytes of signature}$
 - ...
 - $\text{path}[h-1] = \text{next } m \text{ bytes of signature}$
3. $K_c = \text{candidate public key computed by applying Algorithm 4b to the signature lmots_signature, the message, and the}$

identifiers I , q

4. compute the candidate LMS root value T_c as follows:

```
node_num = 2h + q
tmp = H(I || u32str(node_num) || u16str(D_LEAF) || Kc)
i = 0
while (node_num > 1) {
  if (node_num is odd):
    tmp = H(I || u32str(node_num/2) || u16str(D_INTR) || path[i] || tmp)
  else:
    tmp = H(I || u32str(node_num/2) || u16str(D_INTR) || tmp || path[i])
  node_num = node_num/2
  i = i + 1
}
Tc = tmp
```

5. return T_c

6. Hierarchical signatures

In scenarios where it is necessary to minimize the time taken by the public key generation process, a Hierarchical N-time Signature System (HSS) can be used. This hierarchical scheme, which we describe in this section, uses an LMS scheme as a component. HSS, in essence, utilizes a tree of LMS trees. There is a single LMS tree at level 0 (the root). Each LMS tree at level i is used to sign 2^h objects (where h is the height of trees at level i). If $i < L-1$, then each object will be another LMS tree at level $i+1$; if $i = L-1$, we've reached the bottom of the HSS tree, and so each object is an individual message. The HSS public key contains the public key of the LMS tree at the root, and an HSS signature is associated with a path from the root of the HSS tree to the leaf.

Compared to LMS, HSS has a much reduced public key generation time, as only the root tree needs to be generated prior to the distribution of the HSS public key. For example, a $L=3$ tree with $h=10$ at each

level would have 1 level 0 LMS tree, 2^{10} level 1 LMS trees and 2^{20} level 2 LMS trees. Only 1024 OTS public keys need to be computed to generate the HSS public key (as you need to compute only the level 0 LMS tree to compute that value; you can, of course, decide to compute the initial level 1 and level 2 LMS trees). And, the 2^{20} level 2

LMS trees can jointly sign a total of over a billion messages. In contrast, a single LMS tree that could sign a billion messages would require a billion OTS public keys to be computed first (even if $h=30$ were allowed in a supported parameter set).

Each level of the hierarchy is associated with a distinct LMS public key, private key, signature, and identifier. The number of levels is denoted L , and is between one and eight, inclusive. The following notation is used, where i is an integer between 0 and $L-1$ inclusive, and the root of the hierarchy is level 0:

$prv[i]$ is the LMS private key of the i -th level,

$pub[i]$ is the LMS public key of the i -th level (which includes the identifier I as well as the key value K),

$sig[i]$ is the LMS signature generated using the private key of the i -th level,

In this section, we say that an N -time private key is exhausted when it has generated N signatures, and thus it can no longer be used for signing.

HSS allows $L=1$, in which case the HSS public key and signature formats are essentially the LMS public key and signature formats, prepended by a fixed field. Since HSS with $L=1$ has very little overhead compared to LMS, all implementations **MUST** support HSS in order to maximize interoperability.

[6.1.](#) Key Generation

When an HSS key pair is generated, the key pair for each level **MUST** have its own identifier I .

To generate an HSS private and public key pair, new LMS private and public keys are generated for $prv[i]$ and $pub[i]$ for $i=0, \dots, L-1$. These key pairs, and their identifiers, **MUST** be generated independently.

The public key of the HSS scheme consists of the number of levels L , followed by $pub[0]$, the public key of the top level.

The HSS private key consists of `prv[0]`, ... , `prv[L-1]`. The values `pub[0]` does not change (and, except for the index `q`, the value of `prv[0]` need not change), though the values of `pub[i]` and `prv[i]` are dynamic for $i > 0$, and are changed by the signature generation algorithm.

Here is some pseudocode that explains this key generation logic

Algorithm 7: Generating an HSS keypair

1. generate L LMS key pairs, as specified in sections [5.2](#) and [5.3](#)
2. sign each child key pair with the private key of its parent:
 $i = 0$
 while ($i < L-1$) {
 `sig[i] = lms_signature(pub[i+1], prv[i])`
 $i = i + 1$
 }
3. return `u32str(L) || pub[0]`

Note that the generation of the non-root LMS key pair, and the operations of step 2 can be delayed until the generation of the first signature, should it be advantageous for the implementation to do so.

[6.2](#). Signature Generation

To sign a message using the private key `prv`, the following steps are performed:

If `prv[L-1]` is exhausted, then determine the smallest integer d such that all of the private keys `prv[d]`, `prv[d+1]`, ... , `prv[L-1]` are exhausted. If d is equal to zero, then the HSS key pair is exhausted, and it MUST NOT generate any more signatures. Otherwise, the key pairs for levels d through $L-1$ must be regenerated during the signature generation process, as follows. For i from d to $L-1$, a new LMS public and private key pair with a new identifier is generated, `pub[i]` and `prv[i]` are set to those values, then the public key `pub[i]` is signed with `prv[i-1]`, and `sig[i-1]` is set to the resulting value.

The message is signed with `prv[L-1]`, and the value `sig[L-1]` is set to that result.

The value of the HSS signature is set as follows. We let `signed_pub_key` denote an array of octet strings, where `signed_pub_key[i] = sig[i] || pub[i+1]`, for i between 0 and N_{spk} -

1, inclusive, where $N_{\text{spk}} = L-1$ denotes the number of signed public keys. Then the HSS signature is $u32str(N_{\text{spk}}) || \text{signed_pub_key}[0] || \dots || \text{signed_pub_key}[N_{\text{spk}}-1] || \text{sig}[N_{\text{spk}}]$.

Note that the number of `signed_pub_key` elements in the signature is indicated by the value `Nspk` that appears in the initial four bytes of the signature.

Here is some pseudocode of the above logic

Algorithm 7a: Generating an HSS signature

1. If the message-signing key `prv[L-1]` is exhausted, regenerate that key pair, together with any parent key pairs that might be necessary. If the root key pair is exhausted, then the HSS key pair is exhausted and it MUST NOT generate any more signatures.

```
d = L
while (prv[d-1].q == 2^(prv[d-1].h)) {
    if (d == 0)
        return FAILURE
    d = d - 1
}
while (d < L) {
    create lms keypair pub[d], prv[d]
    sig[d-1] = lms_signature( pub[d], prv[d-1] )
    d = d + 1
}
```

2. sign the message
`sig[L-1] = lms_signature(msg, prv[L-1])`

3. Create the list of signed public keys
`i = 0;`
while (`i < L-1`) {
 `signed_pub_key[i] = sig[i] || pub[i+1]`
 `i = i + 1`
}

4. return `u32str(L-1) || signed_pub_key[0] || ... || signed_pub_key[L-2] || s`

In the specific case of $L=1$, the format of an HSS signature is

```
u32str(0) || sig[0]
```

In the general case, the format of an HSS signature is

```
u32str(Nspk) || signed_pub_key[0] || ... || signed_pub_key[Nspk-1] || sig[Ns
```

which is equivalent to

```
u32str(Nspk) || sig[0] || pub[1] || ... || sig[Nspk-1] || pub[Nspk] || sig[N
```

[6.3.](#) Signature Verification

To verify a signature `sig` and message using the public key `pub`, the following steps are performed:

The signature `S` is parsed into its components as follows:

```
Nspk = strTou32(first four bytes of S)
if Nspk+1 is not equal to the number of levels L in pub:
    return INVALID
for (i = 0; i < Nspk; i = i + 1) {
    siglist[i] = next LMS signature parsed from S
    publist[i] = next LMS public key parsed from S
}
siglist[Nspk] = next LMS signature parsed from S

key = pub
for (i = 0; i < Nspk; i = i + 1) {
    sig = siglist[i]
    msg = publist[i]
    if (lms_verify(msg, key, sig) != VALID):
        return INVALID
    key = msg
return lms_verify(message, key, siglist[Nspk])
```

Since the length of an LMS signature cannot be known without parsing it, the HSS signature verification algorithm makes use of an LMS

signature parsing routine that takes as input a string consisting of an LMS signature with an arbitrary string appended to it, and returns both the LMS signature and the appended string. The latter is passed on for further processing.

7. Formats

The signature and public key formats are formally defined using the External Data Representation (XDR) [[RFC4506](#)] in order to provide an unambiguous, machine readable definition. For clarity, we also include a private key format as well, though consistency is not needed for interoperability and an implementation MAY use any private key format. Though XDR is used, these formats are simple and easy to

parse without any special tools. An illustration of the layout of data in these objects is provided below. The definitions are as follows:

```
/* one-time signatures */

enum lmots_algorithm_type {
    lmots_reserved      = 0,
    lmots_sha256_n32_w1 = 1,
    lmots_sha256_n32_w2 = 2,
    lmots_sha256_n32_w4 = 3,
    lmots_sha256_n32_w8 = 4
};

typedef opaque bytestring32[32];

struct lmots_signature_n32_p265 {
    bytestring32 C;
    bytestring32 y[265];
};

struct lmots_signature_n32_p133 {
    bytestring32 C;
    bytestring32 y[133];
};

struct lmots_signature_n32_p67 {
```

```

    bytestring32 C;
    bytestring32 y[67];
};

struct lmots_signature_n32_p34 {
    bytestring32 C;
    bytestring32 y[34];
};

union lmots_signature switch (lmots_algorithm_type type) {
    case lmots_sha256_n32_w1:
        lmots_signature_n32_p265 sig_n32_p265;
    case lmots_sha256_n32_w2:
        lmots_signature_n32_p133 sig_n32_p133;
    case lmots_sha256_n32_w4:
        lmots_signature_n32_p67 sig_n32_p67;
    case lmots_sha256_n32_w8:
        lmots_signature_n32_p34 sig_n32_p34;
    default:
        void; /* error condition */
};

```

```

};

/* hash based signatures (hbs) */

enum lms_algorithm_type {
    lms_reserved = 0,
    lms_sha256_n32_h5 = 5,
    lms_sha256_n32_h10 = 6,
    lms_sha256_n32_h15 = 7,
    lms_sha256_n32_h20 = 8,
    lms_sha256_n32_h25 = 9,
};

/* leighton-micali signatures (lms) */

union lms_path switch (lms_algorithm_type type) {
    case lms_sha256_n32_h5:
        bytestring32 path_n32_h5[5];
    case lms_sha256_n32_h10:
        bytestring32 path_n32_h10[10];
};

```

```

case lms_sha256_n32_h15:
    bytestring32 path_n32_h15[15];
case lms_sha256_n32_h20:
    bytestring32 path_n32_h20[20];
case lms_sha256_n32_h25:
    bytestring32 path_n32_h25[25];
default:
    void;      /* error condition */
};

struct lms_signature {
    unsigned int q;
    lmots_signature lmots_sig;
    lms_path nodes;
};

struct lms_key_n32 {
    lmots_algorithm_type ots_alg_type;
    opaque I[16];
    opaque K[32];
};

union lms_public_key switch (lms_algorithm_type type) {
case lms_sha256_n32_h5:
case lms_sha256_n32_h10:
case lms_sha256_n32_h15:
case lms_sha256_n32_h20:

```

```

case lms_sha256_n32_h25:
    lms_key_n32 z_n32;
default:
    void;      /* error condition */
};

/* hierarchical signature system (hss) */

struct hss_public_key {
    unsigned int L;
    lms_public_key pub;
};

struct signed_public_key {

```

```

    lms_signature sig;
    lms_public_key pub;
}

struct hss_signature {
    signed_public_key signed_keys<7>;
    lms_signature sig_of_message;
};

```

8. Rationale

The goal of this note is to describe the LM-OTS, LMS and HSS algorithms following the original references and present the modern security analysis of those algorithms. Other signature methods are out of scope and may be interesting follow-on work.

We adopt the techniques described by Leighton and Micali to mitigate attacks that amortize their work over multiple invocations of the hash function.

The values taken by the identifier *I* across different LMS public/private key pairs are chosen randomly in order to improve security. The analysis of this method in [Fluhrer17] shows that we do not need uniqueness to ensure security; we do need to ensure that we don't have a large number of private keys that use the same *I* value. By randomly selecting 16 byte *I* values, the chance that, out of 2^{64} private keys, 4 or more of them will use the same *I* value is negligible (that is, has probability less than 2^{-128}).

The reason this size was selected was to optimize the Winternitz hash chain operation. With the current settings, the value being hashed is exactly 55 bytes long (for a 32 byte hash function), which SHA-256 can hash in a single hash compression operation. Other hash functions may be used in future specifications; all the ones that we

will be likely to support (SHA-512/256 and the various SHA-3 hashes) would work well with a 16-byte *I* value.

The signature and public key formats are designed so that they are relatively easy to parse. Each format starts with a 32-bit enumeration value that indicates the details of the signature algorithm and provides all of the information that is needed in order

to parse the format.

The Checksum [Section 4.4](#) is calculated using a non-negative integer "sum", whose width was chosen to be an integer number of w-bit fields such that it is capable of holding the difference of the total possible number of applications of the function H as defined in the signing algorithm of [Section 4.5](#) and the total actual number. In the case that the number of times H is applied is 0, the sum is $(2^w - 1) * (8 * n / w)$. Thus for the purposes of this document, which describes signature methods based on $H = \text{SHA256}$ ($n = 32$ bytes) and $w = \{ 1, 2, 4, 8 \}$, the sum variable is a 16-bit non-negative integer for all combinations of n and w. The calculation uses the parameter ls defined in [Section 4.1](#) and calculated in [Appendix B](#), which indicates the number of bits used in the left-shift operation.

[8.1](#). Security string

To improve security against attacks that amortize their effort against multiple invocations of the hash function, Leighton and Micali introduce a "security string" that is distinct for each invocation of that function. Whenever this process computes a hash, the string being hashed will start with a string formed from the below fields. These fields will appear in fixed locations in the value we compute the hash of, and so we list where in the hash these fields would be present. These fields that make up this string are:

I - a 16-byte identifier for the LMS public/private key pair. It MUST be chosen uniformly at random, or via a pseudorandom process, at the time that a key pair is generated, in order to minimize the probability that any specific value of I be used for a large number of different LMS private keys. This is always bytes 0-15 of the value being hashed.

r - in the LMS N-time signature scheme, the node number r associated with a particular node of a hash tree is used as an input to the hash used to compute that node. This value is represented as a 32-bit (four byte) unsigned integer in network byte order. Either r or q (depending on the domain separation parameter) will be bytes 16-19 of the value being hashed.

q - in the LMS N-time signature scheme, each LM-OTS signature is associated with the leaf of a hash tree, and q is set to the leaf number. This ensures that a distinct value of q is used for each distinct LM-OTS public/private key pair. This value is represented as a 32-bit (four byte) unsigned integer in network byte order. Either r or q (depending on the domain separation parameter) will be bytes 16-19 of the value being hashed.

D - a domain separation parameter, which is a two byte identifier that takes on different values in the different contexts in which the hash function is invoked. D occurs in bytes 20, 21 of the the valeu being hashed, and takes on the following values:

D_PBLC = 0x8080 when computing the hash of all of the iterates in the LM-OTS algorithm

D_MSG = 0x8181 when computing the hash of the message in the LM-OTS algorithms

D_LEAF = 0x8282 when computing the hash of the leaf of an LMS tree

D_INTR = 0x8383 when computing the hash of an interior node of an LMS tree

i - a value between 0 and 264; this is used in the LM-OTS scheme, when either computing the iterations of the Winternitz chain, or when using the suggested LM-OTS private key generation process. It is represented as a 16-bit (two-byte) unsigned integer in network byte order.

j - in the LM-OTS scheme, j is the iteration number used when the private key element is being iteratively hashed. It is represented as an 8-bit (one byte) unsigned integer and is present if D is a value between 0 and 264. If present, it occurs at byte 22 of the value being hashed.

C - an n-byte randomizer that is included with the message whenever it is being hashed to improve security. C MUST be chosen uniformly at random, or via a pseudorandom process. It is present if D=D_MSG, and it occurs at bytes 22 to 21+n of the value being hashed.

9. History

This is the eleventh version of this draft. It has the following changes from previous versions:

Internet-Draft

Hash-Based Signatures

April 2018

Version 10

Numerous clarifications and typo corrections.

Version 09

Corrected size of the OTS signature in [section 4.2](#)

Miscellaneous clarifications and typo corrections.

Version 08

Added additional test vector with private key

Added appendix with discussion of parameter set trade-offs

Miscellaneous clarifications and typo corrections.

Version 07

Corrected the LMS public key format specification in [section 5.3](#); the format listed in [section 7](#) was correct.

Corrected the LMS public key generation algorithm in [appendix C](#). The hashes listed in [section 5.3](#) were correct.

Corrected the HSS signature verification algorithm in [section 6.3](#).

Miscellaneous clarifications and typo corrections.

Version 06

Modified the order of the values that were hashed to make it easier to prove security.

Decreased the size of the I LMS public key identifier to 16 bytes.

Version 05

Clarified the L=1 specific case.

Extended the parameter sets to include an H=25 option

A large number of corrections and clarifications

Added a comparison to XMSS and SPHINCS, and citations to those algorithms and to the recent Security Standardization Research

McGrew, et al.

Expires October 7, 2018

[Page 31]

Internet-Draft

Hash-Based Signatures

April 2018

2016 publications on the security of LMS and on the state management in hash-based signatures.

Version 04

Specified that, in the HSS method, the I value was computed from the I value of the parent LM tree. Previous versions had the I value extracted from the public key (which meant that all LM trees of a particular level and public key used the same I value)

Changed the length of the I field based on the parameter set. As noted in the Rationale section, this allows an implementation to compute SHA256 $n=32$ based parameter sets significantly faster.

Modified the XDR of an HSS signature not to use an array of LM signatures; LM signatures are variable length, and XDR doesn't support arrays of variable length structures.

Changed the LMS registry to be in a consistent order with the LM-OTS parameter sets. Also, added LMS parameter sets with height 15 trees

Previous versions

In Algorithms 3 and 4, the message was moved from the initial position of the input to the function H to the final position, in the computation of the intermediate variable Q. This was done to improve security by preventing an attacker that can find a collision in H from taking advantage of that fact via the forward chaining property of Merkle-Damgard.

The Hierarchical Signature Scheme was generalized slightly so that it can use more than two levels.

Several points of confusion were corrected; these had resulted from incomplete or inconsistent changes from the Merkle approach

of the earlier draft to the Leighton-Micali approach.

This section is to be removed by the RFC editor upon publication.

10. IANA Considerations

The Internet Assigned Numbers Authority (IANA) is requested to create two registries: one for OTS signatures, which includes all of the LM-OTS signatures as defined in [Section 3](#), and one for Leighton-Micali Signatures, as defined in [Section 4](#). Additions to these registries require that a specification be documented in an RFC or another permanent and readily available reference in sufficient detail that

McGrew, et al.

Expires October 7, 2018

[Page 32]

Internet-Draft

Hash-Based Signatures

April 2018

interoperability between independent implementations is possible. Each entry in the registry contains the following elements:

- a short name, such as "LMS_SHA256_M32_H10",

- a positive number, and

- a reference to a specification that completely defines the signature method test cases that can be used to verify the correctness of an implementation.

Requests to add an entry to the registry MUST include the name and the reference. The number is assigned by IANA. Submitters SHOULD have their requests reviewed by the IRTF Crypto Forum Research Group (CFRG) at cfrg@ietf.org. Interested applicants that are unfamiliar with IANA processes should visit <http://www.iana.org>.

The numbers between 0xDDDDDDDD (decimal 3,722,304,989) and 0xFFFFFFFF (decimal 4,294,967,295) inclusive, will not be assigned by IANA, and are reserved for private use; no attempt will be made to prevent multiple sites from using the same value in different (and incompatible) ways [[RFC2434](#)].

The LM-OTS registry is as follows.

+-----+-----+-----+			
Name		Reference	Numeric Identifier
+-----+-----+-----+			
LMOTS_SHA256_N32_W1		Section 4	0x00000001

LMOTS_SHA256_N32_W2	Section 4	0x00000002
LMOTS_SHA256_N32_W4	Section 4	0x00000003
LMOTS_SHA256_N32_W8	Section 4	0x00000004

Table 3

The LMS registry is as follows.

Name	Reference	Numeric Identifier
LMS_SHA256_M32_H5	Section 5	0x00000005
LMS_SHA256_M32_H10	Section 5	0x00000006
LMS_SHA256_M32_H15	Section 5	0x00000007
LMS_SHA256_M32_H20	Section 5	0x00000008
LMS_SHA256_M32_H25	Section 5	0x00000009

Table 4

An IANA registration of a signature system does not constitute an endorsement of that system or its security.

[11](#). Intellectual Property

This draft is based on U.S. patent 5,432,852, which issued over

twenty years ago and is thus expired.

11.1. Disclaimer

This document is not intended as legal advice. Readers are advised to consult with their own legal advisers if they would like a legal interpretation of their rights.

The IETF policies and processes regarding intellectual property and patents are outlined in [[RFC3979](#)] and [[RFC4879](#)] and at <https://datatracker.ietf.org/ipr/about>.

12. Security Considerations

The hash function H MUST have second preimage resistance: it must be computationally infeasible for an attacker that is given one message M to be able to find a second message M' such that $H(M) = H(M')$.

The security goal of a signature system is to prevent forgeries. A successful forgery occurs when an attacker who does not know the private key associated with a public key can find a message (distinct from all previously signed ones) and signature that is valid with that public key (that is, the Signature Verification algorithm applied to that signature and message and public key will return VALID). Such an attacker, in the strongest case, may have the

ability to forge valid signatures for an arbitrary number of other messages.

LMS is provably secure in the random oracle model, where the hash compression function is considered the random oracle, as shown by [[Fluhrer17](#)]. Corollary 1 of that paper states:

If we have no more than 2^{64} randomly chosen LMS private keys, allow the attacker access to a signing oracle and a SHA-256 hash compression oracle, and allow a maximum of 2^{120} hash compression computations, then the probability of an attacker being able to generate a single forgery against any of those LMS keys is less than 2^{-129} .

Many of the objects within the public key and the signature start

with a typecode. A verifier MUST check each of these typecodes, and a verification operation on a signature with an unknown type, or a type that does not correspond to the type within the public key MUST return INVALID. The expected length of a variable-length object can be determined from its typecode, and if an object has a different length, then any signature computed from the object is INVALID.

12.1. Hash Formats

The format of the inputs to the hash function H have the property that each invocation of that function has an input that is repeated by a small bounded number of other inputs (due to potential repeats of the I value), and in particular, will vary somewhere in the first 23 bytes of the value being hashed. This property is important for a proof of security in the random oracle model.

The formats used during key generation and signing

```
I || u32str(q) || u16str(i) || u8str(j) || tmp
I || u32str(q) || u16str(D_PBLC) || y[0] || ... || y[p-1]
I || u32str(q) || u16str(D_MESG) || C || message
I || u32str(r) || u16str(D_LEAF) || OTS_PUB_HASH[r-2^h]
I || u32str(r) || u16str(D_INTR) || T[2*r] || T[2*r+1]
I || u32str(q) || u16str(j) || u8str(0xff) || SEED
```

Each hash type listed is distinct; at locations 20, 21 of each hash, there exists either a fixed value D_PBLC, D_MESG, D_LEAF, D_INTR, or a 16 bit value (i or j). These fixed values are distinct from each other, and are large (over 32768), while the 16 bit values are small (currently no more than 265; possibly being slightly larger if larger hash functions are supported); hence the hash invocations with i/j will not collide any of the D_PBLC, D_MESG, D_LEAF, D_INTR hashes. The only other collision possibility is the Winternitz chain hash

colliding with the recommended pseudorandom key generation process; here, at location 22, the Winternitz chain function has the value u8str(j), where j is a value between 0 and 254, while location 22 of the recommended pseudorandom key generation process has value 255.

For the Winternitz chaining function, D_PBLC, and D_MESG, the value of I || u32str(q) is distinct for each LMS leaf (or equivalently, for each q value). For the Winternitz chaining function, the value of

$u16str(i) || u8str(j)$ is distinct for each invocation of H for a given leaf. For D_PBLC and D_MSG , the input format is used only once for each value of q , and thus distinctness is assured. The formats for D_INTR and D_LEAF are used exactly once for each value of r , which ensures their distinctness. For the recommended pseudorandom key generation process, for a given value of I , q and j are distinct for each invocation of H .

The value of I is chosen uniformly at random from the set of all 128 bit strings. If 2^{64} public keys are generated (and hence 2^{64} random I values), there is a nontrivial probability of a duplicate (which would imply duplicate prefixes. However, there will be an extremely high probability there will not be a four-way collision (that is, any I value used for four distinct LMS keys; probability $< 2^{-132}$), and hence the number of repeats for any specific prefix will be limited to 3. This is shown (in [[Fluhrer17](#)]) to have only a limited effect on the security of the system.

12.2. Stateful signature algorithm

The LMS signature system, like all N-time signature systems, requires that the signer maintain state across different invocations of the signing algorithm, to ensure that none of the component one-time signature systems are used more than once. This section calls out some important practical considerations around this statefulness.

In a typical computing environment, a private key will be stored in non-volatile media such as on a hard drive. Before it is used to sign a message, it will be read into an application's Random Access Memory (RAM). After a signature is generated, the value of the private key will need to be updated by writing the new value of the private key into non-volatile storage. It is essential for security that the application ensure that this value is actually written into that storage, yet there may be one or more memory caches between it and the application. Memory caching is commonly done in the file system, and in a physical memory unit on the hard disk that is dedicated to that purpose. To ensure that the updated value is written to physical media, the application may need to take several special steps. In a POSIX environment, for instance, the `O_SYNC` flag (for the `open()` system call) will cause invocations of the `write()`

system call to block the calling process until the data has been

written to the underlying hardware. However, if that hardware has its own memory cache, it must be separately dealt with using an operating system or device specific tool such as hdparm to flush the on-drive cache, or turn off write caching for that drive. Because these details vary across different operating systems and devices, this note does not attempt to provide complete guidance; instead, we call the implementer's attention to these issues.

When hierarchical signatures are used, an easy way to minimize the private key synchronization issues is to have the private key for the second level resident in RAM only, and never write that value into non-volatile memory. A new second level public/private key pair will be generated whenever the application (re)starts; thus, failures such as a power outage or application crash are automatically accommodated. Implementations SHOULD use this approach wherever possible.

[12.3.](#) Security of LM-OTS Checksum

To show the security of LM-OTS checksum, we consider the signature y of a message with a private key x and let $h = H(\text{message})$ and $c = \text{Cksm}(H(\text{message}))$ (see [Section 4.5](#)). To attempt a forgery, an attacker may try to change the values of h and c . Let h' and c' denote the values used in the forgery attempt. If for some integer j in the range 0 to u , where $u = \text{ceil}(8 \times n/w)$ is the size of the range that the checksum value can cover), inclusive,

$$a' = \text{coef}(h', j, w),$$

$$a = \text{coef}(h, j, w), \text{ and}$$

$$a' > a$$

then the attacker can compute $F^{a'}(x[j])$ from $F^a(x[j]) = y[j]$ by iteratively applying function F to the j -th term of the signature an additional $(a' - a)$ times. However, as a result of the increased number of hashing iterations, the checksum value c' will decrease from its original value of c . Thus a valid signature's checksum will have, for some number k in the range u to $(p-1)$, inclusive,

$$b' = \text{coef}(c', k, w),$$

$$b = \text{coef}(c, k, w), \text{ and}$$

$$b' < b$$

Due to the one-way property of F , the attacker cannot easily compute $F^b(x[k])$ from $F^b(x[k]) = y[k]$.

13. Comparison with other work

The eXtended Merkle Signature Scheme (XMSS) [XMSS] is similar to HSS in several ways. Both are stateful hash based signature schemes, and both use a hierarchical approach, with a Merkle tree at each level of the hierarchy. XMSS signatures are slightly shorter than HSS signatures, for equivalent security and an equal number of signatures.

HSS has several advantages over XMSS. HSS operations are roughly four times faster than the comparable XMSS ones, when SHA256 is used as the underlying hash. This occurs because the hash operation done as a part of the Winternitz iterations dominates performance, and XMSS performs four compression function invocations (two for the PRF, two for the F function) where HSS needs only perform one. Additionally, HSS is somewhat simpler (as each hash invocation is just a prefix followed by the data being hashed).

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McGrew, et al.

Expires October 7, 2018

[Page 39]

Internet-Draft

Hash-Based Signatures

April 2018

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[Appendix A](#). Pseudorandom Key Generation

An implementation MAY use the following pseudorandom process for generating an LMS private key.

SEED is an m-byte value that is generated uniformly at random at the start of the process,

I is LMS key pair identifier,

q denotes the LMS leaf number of an LM-OTS private key,

x_q denotes the x array of private elements in the LM-OTS private key with leaf number q,

j is an index of the private key element, and

H is the hash function used in LM-OTS.

The elements of the LM-OTS private keys are computed as:

$$x_q[j] = H(I \parallel u32str(q) \parallel u16str(j) \parallel u8str(0xff) \parallel SEED).$$

This process stretches the m-byte random value SEED into a (much larger) set of pseudorandom values, using a unique counter in each invocation of H. The format of the inputs to H are chosen so that they are distinct from all other uses of H in LMS and LM-OTS. A careful reader will note that this is similar to the hash we perform when iterating through the Winternitz chain; however in that chain, the iteration index will vary between 0 and 254 maximum (for W=8), while the corresponding value in this formula is 255. This algorithm is included in the proof of security in [Fluhrer17] and hence this method is safe when used within the LMS system; however any other

cryptographical secure method of generating private keys would also be safe.

[Appendix B](#). LM-OTS Parameter Options

The LM-OTS one time signature method uses several internal parameters, which are a function of the selected parameter set. These internal parameters set:

p - This is the number of independent Winternitz chains used in the signature; it will be the number of w-bit digits needed to hold the n-bit hash (u in the below equations), along with the number of digits needed to hold the checksum (v in the below equations)

ls - This is the size of the shift needed to move the checksum so that it appears in the checksum digits

The parameters ls, and p are computed as follows:

$$\begin{aligned} u &= \text{ceil}(8*n/w) \\ v &= \text{ceil}((\text{floor}(\lg((2^w - 1) * u)) + 1) / w) \\ ls &= 16 - (v * w) \\ p &= u + v \end{aligned}$$

Here u and v represent the number of w -bit fields required to contain the hash of the message and the checksum byte strings, respectively. And as the value of p is the number of w -bit elements of $(H(\text{message}) || \text{Cksm}(H(\text{message})))$, it is also equivalently the number of byte strings that form the private key and the number of byte strings in the signature. The value 16 in the ls computation of ls corresponds to the 16 bits value used for the sum variable in Algorithm 2 in [Section 4.4](#)

A table illustrating various combinations of n and w with the associated values of u , v , ls , and p is provided in Table 5.

Hash Length in Bytes (n)	Winternitz Parameter (w)	w -bit Elements in Hash (u)	w -bit Elements in Checksum (v)	Left Shift (ls)	Total Number of w -bit Elements (p)
32	1	256	9	7	265
32	2	128	5	6	133
32	4	64	3	4	67
32	8	32	2	0	34

Table 5

[Appendix C](#). An iterative algorithm for computing an LMS public key

The LMS public key can be computed using the following algorithm or any equivalent method. The algorithm uses a stack of hashes for data. It also makes use of a hash function with the typical init/update/final interface to hash functions; the result of the invocations `hash_init()`, `hash_update(N[1])`, `hash_update(N[2])`, ..., `hash_update(N[n])`, `v = hash_final()`, in that order, is identical to that of the invocation of `H(N[1] || N[2] || ... || N[n])`.

Generating an LMS Public Key from an LMS Private Key

```
for ( i = 0; i < 2^h; i = i + 1 ) {
    r = i + num_lmots_keys;
    temp = H(I || u32str(r) || u16str(D_LEAF) || OTS_PUB_HASH[i])
    j = i;
    while (j % 2 == 1) {
        r = (r - 1)/2;
        j = (j-1) / 2;
        left_side = pop(data stack);
        temp = H(I || u32str(r) || u16str(D_INTR) || left_side || temp)
```



```

    }
    push temp onto the data stack
}
public_key = pop(data stack)

```

Note that this pseudocode expects that all 2^h leaves of the tree have equal depth; that is, `num_lmots_keys` to be a power of 2. The maximum depth of the stack will be $h-1$ elements, that is, a total of $(h-1)*n$ bytes; for the currently defined parameter sets, this will never be more than 768 bytes of data.

[Appendix D](#). Method for deriving authentication path for a signature

The LMS signature consists of `u32str(q) || lmots_signature || u32str(type) || path[0] || path[1] || ... || path[h-1]`. This appendix shows one method of constructing this signature, assuming that the implementation has stored the `T[]` array that was used to construct the public key. Note that this is not the only possible method; other methods exist which don't assume that you have the entire `T[]` array in memory. To construct a signature, you perform the following algorithm:

Generating an LMS Signature

1. set `type` to the typecode of the LMS algorithm

2. extract h from the typecode according to table 2

3. create the LM-OTS signature for the message:

```
ots_signature = lmots_sign(message, LMS_PRIV[q])
```

4. compute the array path as follows:

```
i = 0
r = 2^h + q
while (i < h) {
    temp = (r / 2^i) xor 1
    path[i] = T[temp]
    i = i + 1
}
```

5. $S = \text{u32str}(q) \parallel \text{ots_signature} \parallel \text{u32str}(\text{type}) \parallel \text{path}[0] \parallel \text{path}[1] \parallel \dots$

6. $q = q + 1$

7. return S

where 'xor' is the bitwise exclusive-or operation, and / is integer division (that is, rounded down to an integer value)

[Appendix E](#). Example Implementation

An example implementation can be found online at

<http://github.com/cisco/hash-sigs>.

[Appendix F](#). Parameter Set Recommendations

As for guidance as to the number of LMS level, and the size of each, any discussion of performance is implementation specific. In general, the sole drawback for a single LMS tree is the time it takes to generate the public key; as every LM-OTS public key needs to be generated, the time this takes can be substantial. For a two level tree, only the top level LMS tree and the initial bottom level LMS tree needs to be generated initially (before the first signature is generated); this will in general be significantly quicker.

To give a general idea on the trade-offs available, we include some measurements taken with the github.com/cisco/hash-sigs LMS implementation, taken on a 3.3 GHz Xeon processor, with threading enabled. We tried various parameter sets, all with $W=8$ (which minimizes signature size, while increasing time). These are here to

give a guideline as to what's possible; for the computational time, your mileage may vary, depending on the computing resources you have. The machine I have does not have the SHA-256 extensions; you could possibly do significantly better.

ParmSet	KeyGenTime	SigSize	KeyLifetime
15	6 sec	1616	30 seconds
20	3 min	1776	16 minutes
25	1.5 hour	1936	9 hours
15/10	6 sec	3172	9 hours
15/15	6 sec	3332	12 days
20/10	3 min	3332	12 days
20/15	3 min	3492	1 year
25/10	1.5 hour	3492	1 year
25/15	1.5 hour	3652	34 years

ParmSet: this is the height of the Merkle tree(s); parameter sets listed as a single integer consists of a single Merkle tree of that height; parameter sets that consist of two trees are listed as x/y, with x being the height of the top level Merkle tree, and y being the bottom level.

KeyGenTime: the measured key generation time; that is, the time needed to generate the public private key pair.

SigSize: the size of a signature (in bytes)

KeyLifetime: the lifetime of a key, assuming we generated 1000 signatures per second. In practice, we're not likely to get anywhere close to 1000 signatures per second sustained; if you have a more appropriate figure for your scenario, this column is pretty easy to recompute.

As for signature generation or verification times, those are moderately insensitive to the above parameter settings (except for the Winternitz setting, and the number of Merkle trees for verification). Tests on the same machine (without multithreading) gave approximately 4msec to sign a short message, 2.6msec to verify; these tests used a two level ParmSet; a single level would approximately halve the verification time. All times can be significantly improved (by maybe a factor of 8) by using a parameter set with W=4; however that also about doubles the signature size.

[Appendix G](#). Test Cases

This section provides test cases that can be used to verify or debug an implementation. This data is formatted with the name of the

elements on the left, and the value of the elements on the right, in

hexadecimal. The concatenation of all of the values within a public key or signature produces that public key or signature, and values that do not fit within a single line are listed across successive lines.

Test Case 1 Public Key

```
-----
HSS public key
levels      00000002
-----
LMS type    00000005          # LM_SHA256_M32_H5
LMOTS type  00000004          # LMOTS_SHA256_N32_W8
I           61a5d57d37f5e46bfb7520806b07a1b8
K           50650e3b31fe4a773ea29a07f09cf2ea
           30e579f0df58ef8e298da0434cb2b878
-----
-----
```

Test Case 1 Message

```
-----
Message      54686520706f77657273206e6f742064 |The powers not d|
              656c65676174656420746f2074686520 |elegated to the |
              556e6974656420537461746573206279 |United States by|
              2074686520436f6e737469747574696f | the Constitutio|
              6e2c206e6f722070726f686962697465 |n, nor prohibite|
              6420627920697420746f207468652053 |d by it to the S|
              74617465732c20617265207265736572 |tates, are reser|
              76656420746f20746865205374617465 |ved to the State|
              7320726573706563746976656c792c20 |s respectively, |
              6f7220746f207468652070656f706c65 |or to the people|
              2e0a                                |..|
-----
```

Test Case 1 Signature

```
-----
HSS signature
Nspk      00000001
```

sig[0]:

LMS signature

q 00000005

LMOTS signature

LMOTS type 00000004

LMOTS_SHA256_N32_W8

C d32b56671d7eb98833c49b433c272586

y[0]	bc4a1c8a8970528ffa04b966f9426eb9 965a25bfd37f196b9073f3d4a232feb6 9128ec45146f86292f9dff9610a7bf95
y[1]	a64c7f60f6261a62043f86c70324b770 7f5b4a8a6e19c114c7be866d488778a0
y[2]	e05fd5c6509a6e61d559cf1a77a970de 927d60c70d3de31a7fa0100994e162a2
y[3]	582e8ff1b10cd99d4e8e413ef469559f 7d7ed12c838342f9b9c96b83a4943d16
y[4]	81d84b15357ff48ca579f19f5e71f184 66f2bbef4bf660c2518eb20de2f66e3b
y[5]	14784269d7d876f5d35d3fbfc7039a46 2c716bb9f6891a7f41ad133e9e1f6d95
y[6]	60b960e7777c52f060492f2d7c660e14 71e07e72655562035abc9a701b473ecb
y[7]	c3943c6b9c4f2405a3cb8bf8a691ca51 d3f6ad2f428bab6f3a30f55dd9625563
y[8]	f0a75ee390e385e3ae0b906961ecf41a e073a0590c2eb6204f44831c26dd768c
y[9]	35b167b28ce8dc988a3748255230cef9 9ebf14e730632f27414489808afab1d1
y[10]	e783ed04516de012498682212b078105 79b250365941bcc98142da13609e9768
y[11]	aaf65de7620dabec29eb82a17fde35af 15ad238c73f81bdb8dec2fc0e7f93270
y[12]	1099762b37f43c4a3c20010a3d72e2f6 06be108d310e639f09ce7286800d9ef8
y[13]	a1a40281cc5a7ea98d2adc7c7400c2fe 5a101552df4e3cccf0cbf2ddf5dc677
y[14]	9cbbc68fee0c3efe4ec22b83a2caa3e4 8e0809a0a750b73ccdcf3c79e6580c15
y[15]	4f8a58f7f24335eec5c5eb5e0cf01dcf 4439424095fceb077f66ded5bec73b27

y[16]	c5b9f64a2a9af2f07c05e99e5cf80f00 252e39db32f6c19674f190c9fbc506d8
y[17]	26857713afd2ca6bb85cd8c107347552 f30575a5417816ab4db3f603f2df56fb
y[18]	c413e7d0acd8bdd81352b2471fc1bc4f 1ef296fea1220403466b1afe78b94f7e
y[19]	cf7cc62fb92be14f18c2192384ebceaf 8801afdf947f698ce9c6ceb696ed70e9
y[20]	e87b0144417e8d7baf25eb5f70f09f01 6fc925b4db048ab8d8cb2a661ce3b57a
y[21]	da67571f5dd546fc22cb1f97e0ebd1a6 5926b1234fd04f171cf469c76b884cf3
y[22]	115cce6f792cc84e36da58960c5f1d76 0f32c12faef477e94c92eb75625b6a37
y[23]	1efc72d60ca5e908b3a7dd69fef02491

y[24]	50e3eebdfed39cbdc3ce9704882a2072 c75e13527b7a581a556168783dc1e975 45e31865ddc46b3c957835da252bb732
y[25]	8d3ee2062445dfb85ef8c35f8e1f3371 af34023cef626e0af1e0bc017351aae2
y[26]	ab8f5c612ead0b729a1d059d02bfe18e fa971b7300e882360a93b025ff97e9e0
y[27]	eec0f3f3f13039a17f88b0cf808f4884 31606cb13f9241f40f44e537d302c64a
y[28]	4f1f4ab949b9feefadcb71ab50ef27d6 d6ca8510f150c85fb525bf25703df720
y[29]	9b6066f09c37280d59128d2f0f637c7d 7d7fad4ed1c1ea04e628d221e3d8db77
y[30]	b7c878c9411cafc5071a34a00f4cf077 38912753dfce48f07576f0d4f94f42c6
y[31]	d76f7ce973e9367095ba7e9a3649b7f4 61d9f9ac1332a4d1044c96aefee67676
y[32]	401b64457c54d65fef6500c59cdfb69a f7b6dddfcb0f086278dd8ad0686078df
y[33]	b0f3f79cd893d314168648499898fbc0 ced5f95b74e8ff14d735cdea968bee74

LMS type	00000005	# LM_SHA256_M32_H5
path[0]	d8b8112f9200a5e50c4a262165bd342c d800b8496810bc716277435ac376728d	
path[1]	129ac6eda839a6f357b5a04387c5ce97	

```

path[2]      382a78f2a4372917eefcbf93f63bb591
             12f5dbe400bd49e4501e859f885bf073
             6e90a509b30a26bfac8c17b5991c157e
path[3]      b5971115aa39efd8d564a6b90282c316
             8af2d30ef89d51bf14654510a12b8a14
path[4]      4cca1848cf7da59cc2b3d9d0692dd2a2
             0ba3863480e25b1b85ee860c62bf5136
-----
LMS public key
LMS type      00000005                      # LM_SHA256_M32_H5
LMOTS type    00000004                      # LMOTS_SHA256_N32_W8
I             d2f14ff6346af964569f7d6cb880a1b6
K             6c5004917da6eafe4d9ef6c6407b3db0
             e5485b122d9ebe15cda93cfec582d7ab
-----
final_signature:
-----
LMS signature
q             0000000a
-----
LMOTS signature
LMOTS type    00000004                      # LMOTS_SHA256_N32_W8

```

```

C             0703c491e7558b35011ece3592eaa5da
             4d918786771233e8353bc4f62323185c
y[0]          95cae05b899e35dff71705470620998
             8ebfdf6e37960bb5c38d7657e8bffeef
y[1]          9bc042da4b4525650485c66d0ce19b31
             7587c6ba4bffcc428e25d08931e72dfb
y[2]          6a120c5612344258b85efdb7db1db9e1
             865a73caf96557eb39ed3e3f426933ac
y[3]          9eeddb03a1d2374af7bf771855774562
             37f9de2d60113c23f846df26fa942008
y[4]          a698994c0827d90e86d43e0df7f4bfcd
             b09b86a373b98288b7094ad81a0185ac
y[5]          100e4f2c5fc38c003c1ab6fea479eb2f
             5ebe48f584d7159b8ada03586e65ad9c
y[6]          969f6aecbfe44cf356888a7b15a3ff07
             4f771760b26f9c04884ee1faa329fbf4
y[7]          e61af23aee7fa5d4d9a5dfcf43c4c26c
             e8aea2ce8a2990d7ba7b57108b47dabf
y[8]          beadb2b25b3cacc1ac0cef346cbb90fb

```

y[9]	044beee4fac2603a442bdf7e507243b7 319c9944b1586e899d431c7f91bcccc8 690dbf59b28386b2315f3d36ef2eaa3c
y[10]	f30b2b51f48b71b003dfb08249484201 043f65f5a3ef6bbd61ddfee81aca9ce6
y[11]	0081262a00000480dcbc9a3da6fbef5c 1c0a55e48a0e729f9184fcb1407c3152
y[12]	9db268f6fe50032a363c9801306837fa fabdf957fd97eafc80dbd165e435d0e2
y[13]	dfd836a28b354023924b6fb7e48bc0b3 ed95eea64c2d402f4d734c8dc26f3ac5
y[14]	91825daef01eae3c38e3328d00a77dc6 57034f287ccb0f0e1c9a7cbdc828f627
y[15]	205e4737b84b58376551d44c12c3c215 c812a0970789c83de51d6ad787271963
y[16]	327f0a5fbb6b5907dec02c9a90934af5 a1c63b72c82653605d1dcce51596b3c2
y[17]	b45696689f2eb382007497557692caac 4d57b5de9f5569bc2ad0137fd47fb47e
y[18]	664fcb6db4971f5b3e07aceda9ac130e 9f38182de994cff192ec0e82fd6d4cb7
y[19]	f3fe00812589b7a7ce51544045643301 6b84a59bec6619a1c6c0b37dd1450ed4
y[20]	f2d8b584410ceda8025f5d2d8dd0d217 6fc1cf2cc06fa8c82bed4d944e71339e
y[21]	ce780fd025bd41ec34ebff9d4270a322 4e019fcb444474d482fd2dbe75efb203
y[22]	89cc10cd600abb54c47ede93e08c114e db04117d714dc1d525e11bed8756192f

y[23]	929d15462b939ff3f52f2252da2ed64d 8fae88818b1efa2c7b08c8794fb1b214
y[24]	aa233db3162833141ea4383f1a6f120b e1db82ce3630b3429114463157a64e91
y[25]	234d475e2f79cbf05e4db6a9407d72c6 bff7d1198b5c4d6aad2831db61274993
y[26]	715a0182c7dc8089e32c8531deed4f74 31c07c02195eba2ef91efb5613c37af7
y[27]	ae0c066babcb69369700e1dd26eddc0d2 16c781d56e4ce47e3303fa73007ff7b9
y[28]	49ef23be2aa4dbf25206fe45c20dd888 395b2526391a724996a44156beac8082


```

y[29]      12858792bf8e74cba49dee5e8812e019
           da87454bfff9e847ed83db07af3137430
y[30]      82f880a278f682c2bd0ad6887cb59f65
           2e155987d61bbf6a88d36ee93b6072e6
y[31]      656d9ccbaae3d655852e38deb3a2dcf8
           058dc9fb6f2ab3d3b3539eb77b248a66
y[32]      1091d05eb6e2f297774fe6053598457c
           c61908318de4b826f0fc86d4bb117d33
y[33]      e865aa805009cc2918d9c2f840c4da43
           a703ad9f5b5806163d7161696b5a0adc
-----
LMS type   00000005                                # LM_SHA256_M32_H5
path[0]    d5c0d1bebb06048ed6fe2ef2c6cef305
           b3ed633941ebc8b3bec9738754cddd60
path[1]    e1920ada52f43d055b5031cee6192520
           d6a5115514851ce7fd448d4a39fae2ab
path[2]    2335b525f484e9b40d6a4a969394843b
           dc6fd14c48e8015e08ab92662c05c6e9
path[3]    f90b65a7a6201689999f32bfd368e5e3
           ec9cb70ac7b8399003f175c40885081a
path[4]    09ab3034911fe125631051df0408b394
           6b0bde790911e8978ba07dd56c73e7ee

```

Test Case 2 Private Key

```

-----
(note: procedure in Appendix A is used)
SEED      000102030405060708090a0b0c0d0e0f
           101112131415161718191a1b1c1d1e1f
I         d08fabd4a2091ff0a8cb4ed834e74534
-----
-----

```

Test Case 2 Public Key

```

-----
HSS public key
levels      00000002

```

```

-----
LMS type      00000006                # LM_SHA256_M32_H10
LMOTS type    00000003                # LMOTS_SHA256_N32_W4
I             d08fabd4a2091ff0a8cb4ed834e74534
K             32a58885cd9ba0431235466bff9651c6
              c92124404d45fa53cf161c28f1ad5a8e
-----
-----

```

Test Case 2 Message

```

-----
Message      54686520656e756d65726174696f6e20 The enumeration
              696e2074686520436f6e737469747574 in the Constitut
              696f6e2c206f66206365727461696e20 ion, of certain
              7269676874732c207368616c6c206e6f rights, shall no
              7420626520636f6e7374727565642074 t be construed t
              6f2064656e79206f7220646973706172 o deny or dispar
              616765206f7468657273207265746169 age others retai
              6e6564206279207468652070656f706c ned by the peopl
              652e0a                             e..
-----

```

Test Case 2 Signature

```

-----
HSS signature
Nspk         00000001
sig[0]:
-----
LMS signature
q            00000003
-----
LMOTS signature
LMOTS type    00000003                # LMOTS_SHA256_N32_W4
C             3d46bee8660f8f215d3f96408a7a64cf
              1c4da02b63a55f62c666ef5707a914ce
y[0]          0674e8cb7a55f0c48d484f31f3aa4af9
              719a74f22cf823b94431d01c926e2a76
y[1]          bb71226d279700ec81c9e95fb11a0d10
              d065279a5796e265ae17737c44eb8c59
y[2]          4508e126a9a7870bf4360820bdeb9a01
              d9693779e416828e75bddd7d8c70d50a

```

y[3]	0ac8ba39810909d445f44cb5bb58de737e60cb4345302786ef2c6b14af212ca1
y[4]	9edea3bfcfe8baa6621ce88480df2371dd37add732c9de4ea2ce0dffa53c926
y[5]	49a18d39a50788f4652987f226a1d48168205df6ae7c58e049a25d4907edc1aa
y[6]	90da8aa5e5f7671773e941d8055360215c6b60dd35463cf2240a9c06d694e9cb
y[7]	54e7b1e1bf494d0d1a28c0d31acc75161f4f485dfd3cb9578e836ec2dc722f37
y[8]	ed30872e07f2b8bd0374eb57d22c614e09150f6c0d8774a39a6e168211035dc5
y[9]	2988ab46eaca9ec597fb18b4936e66ef2f0df26e8d1e34da28cbb3af75231372
y[10]	0c7b345434f72d65314328bbb030d0f0f6d5e47b28ea91008fb11b05017705a8
y[11]	be3b2adb83c60a54f9d1d1b2f476f9e393eb5695203d2ba6ad815e6a111ea293
y[12]	dcc21033f9453d49c8e5a6387f588b1ea4f706217c151e05f55a6eb7997be09d
y[13]	56a326a32f9cba1fbe1c07bb49fa04cecf9df1a1b815483c75d7a27cc88ad1b1
y[14]	238e5ea986b53e087045723ce16187eda22e33b2c70709e53251025abde89396
y[15]	45fc8c0693e97763928f00b2e3c75af3942d8ddaee81b59a6f1f67efda0ef81d
y[16]	11873b59137f67800b35e81b01563d187c4a1575a1acb92d087b517a8833383f
y[17]	05d357ef4678de0c57ff9f1b2da61dfd e5d88318bcdde4d9061cc75c2de3cd47
y[18]	40dd7739ca3ef66f1930026f47d9ebaa713b07176f76f953e1c2e7f8f271a6ca
y[19]	375dbfb83d719b1635a7d8a13891957944b1c29bb101913e166e11bd5f34186f
y[20]	a6c0a555c9026b256a6860f4866bd6d0b5bf90627086c6149133f8282ce6c9b3
y[21]	622442443d5eca959d6c14ca8389d12c4068b503e4e3c39b635bea245d9d05a2
y[22]	558f249c9661c0427d2e489ca5b5dde220a90333f4862aec793223c781997da9
y[23]	8266c12c50ea28b2c438e7a379eb106eca0c7fd6006e9bf612f3ea0a454ba3bd
y[24]	b76e8027992e60de01e9094fddeb3349883914fb17a9621ab929d970d101e45f
y[25]	8278c14b032bcab02bd15692d21b6c5c204abbf077d465553bd6eda645e6c306
y[26]	5d33b10d518a61e15ed0f092c32226281a29c8a0f50cde0a8c66236e29c2f310

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Hash-Based Signatures

April 2018

y[27]	a375cebda1dc6bb9a1a01dae6c7aba8e bedc6371a7d52aacb955f83bd6e4f84d
y[28]	2949dcc198fb77c7e5cdf6040b0f84fa f82808bf985577f0a2acf2ec7ed7c0b0
y[29]	ae8a270e951743ff23e0b2dd12e9c3c8 28fb5598a22461af94d568f29240ba28
y[30]	20c4591f71c088f96e095dd98beae456 579ebba36f6d9ca2613d1c26eee4d8c
y[31]	73217ac5962b5f3147b492e8831597fd 89b64aa7fde82e1974d2f6779504dc21
y[32]	435eb3109350756b9fdabe1c6f368081 bd40b27ebcb9819a75d7df8bb07bb05d
y[33]	b1bab705a4b7e37125186339464ad8fa aa4f052cc1272919fde3e025bb64aa8e
y[34]	0eb1fcbfcc25acb5f718ce4f7c2182fb 393a1814b0e942490e52d3bca817b2b2
y[35]	6e90d4c9b0cc38608a6cef5eb153af08 58acc867c9922aed43bb67d7b33acc51
y[36]	9313d28d41a5c6fe6cf3595dd5ee63f0 a4c4065a083590b275788bee7ad875a7
y[37]	f88dd73720708c6c6c0ecf1f43bbaada e6f208557fdc07bd4ed91f88ce4c0de8
y[38]	42761c70c186bfdafafc444834bd3418 be4253a71eaf41d718753ad07754ca3e
y[39]	ffd5960b0336981795721426803599ed 5b2b7516920efcbe32ada4bcf6c73bd2
y[40]	9e3fa152d9adeca36020fdeeee1b7395 21d3ea8c0da497003df1513897b0f547
y[41]	94a873670b8d93bcca2ae47e64424b74 23e1f078d9554bb5232cc6de8aae9b83
y[42]	fa5b9510beb39ccf4b4e1d9c0f19d5e1 7f58e5b8705d9a6837a7d9bf99cd1338
y[43]	7af256a8491671f1f2f22af253bcff54 b673199bdb7d05d81064ef05f80f0153
y[44]	d0be7919684b23da8d42ff3effdb7ca0 985033f389181f47659138003d712b5e
y[45]	c0a614d31cc7487f52de8664916af79c 98456b2c94a8038083db55391e347586
y[46]	2250274a1de2584fec975fb09536792c fbfcb6192856cc76eb5b13dc4709e2f7
y[47]	301ddff26ec1b23de2d188c999166c74 e1e14bbc15f457cf4e471ae13dcbdd9c

y[48]	50f4d646fc6278e8fe7eb6cb5c94100f a870187380b777ed19d7868fd8ca7ceb
y[49]	7fa7d5cc861c5bdac98e7495eb0a2cee c1924ae979f44c5390ebedddc65d6ec1
y[50]	1287d978b8df064219bc5679f7d7b264 a76ff272b2ac9f2f7cfc9fdcfb6a5142

Internet-Draft

Hash-Based Signatures

April 2018

y[51]	8240027afd9d52a79b647c90c2709e06 0ed70f87299dd798d68f4fadd3da6c51
y[52]	d839f851f98f67840b964ebe73f8cec4 1572538ec6bc131034ca2894eb736b3b
y[53]	da93d9f5f6fa6f6c0f03ce43362b8414 940355fb54d3dfdd03633ae108f3de3e
y[54]	bc85a3ff51efeea3bc2cf27e1658f178 9ee612c83d0f5fd56f7cd071930e2946
y[55]	beeecaa04dccea9f97786001475e0294 bc2852f62eb5d39bb9fbee7f5916efe4
y[56]	4a662ecae37ede27e9d6eadfdeb8f8b2 b2dbccbf96fa6dbaf7321fb0e701f4d4
y[57]	29c2f4dcd153a2742574126e5eaccc77 686acf6e3ee48f423766e0fc466810a9
y[58]	05ff5453ec99897b56bc55dd49b99114 2f65043f2d744eeb935ba7f4ef23cf80
y[59]	cc5a8a335d3619d781e7454826df720e ec82e06034c44699b5f0c44a8787752e
y[60]	057fa3419b5bb0e25d30981e41cb1361 322dba8f69931cf42fad3f3bce6ded5b
y[61]	8bfc3d20a2148861b2afc14562ddd27f 12897abf0685288dcc5c4982f8260268
y[62]	46a24bf77e383c7aacab1ab692b29ed8 c018a65f3dc2b87ff619a633c41b4fad
y[63]	b1c78725c1f8f922f6009787b1964247 df0136b1bc614ab575c59a16d089917b
y[64]	d4a8b6f04d95c581279a139be09fcf6e 98a470a0bceca191fce476f9370021cb
y[65]	c05518a7efd35d89d8577c990a5e1996 1ba16203c959c91829ba7497cfffcb4b
y[66]	294546454fa5388a23a22e805a5ca35f 956598848bda678615fec28afd5da61a

LMS type
path[0]

00000006
b326493313053ced3876db9d23714818

LM_SHA256_M32_H10

```
path[1] 1b7173bc7d042cefb4dbe94d2e58cd21
a769db4657a103279ba8ef3a629ca84e
e836172a9c50e51f45581741cf808315
path[2] 0b491cb4ecbbabec128e7c81a46e62a6
7b57640a0a78be1cbf7dd9d419a10cd8
path[3] 686d16621a80816bfdb5bdc56211d72c
a70b81f1117d129529a7570cf79cf52a
path[4] 7028a48538ecdd3b38d3d5d62d262465
95c4fb73a525a5ed2c30524ebb1d8cc8
path[5] 2e0c19bc4977c6898ff95fd3d310b0ba
e71696cef93c6a552456bf96e9d075e3
path[6] 83bb7543c675842bafbfc7cdb88483b3
276c29d4f0a341c2d406e40d4653b7e4
```

```
path[7] d045851acf6a0a0ea9c710b805cccd46
35ee8c107362f0fc8d80c14d0ac49c51
path[8] 6703d26d14752f34c1c0d2c4247581c1
8c2cf4de48e9ce949be7c888e9caebe4
path[9] a415e291fd107d21dc1f084b11582082
49f28f4f7c7e931ba7b3bd0d824a4570
```

LMS public key

LMS type 00000005

LM_SHA256_M32_H5

LMOTS type 00000004

LMOTS_SHA256_N32_W8

I 215f83b7ccb9acbcd08db97b0d04dc2b

K a1cd035833e0e90059603f26e07ad2aa
d152338e7a5e5984bcd5f7bb4eba40b7

final_signature:

LMS signature

q 00000004

LMOTS signature

LMOTS type 00000004

LMOTS_SHA256_N32_W8

C 0eb1ed54a2460d512388cad533138d24
0534e97b1e82d33bd927d201dfc24ebb

y[0] 11b3649023696f85150b189e50c00e98
850ac343a77b3638319c347d7310269d

y[1] 3b7714fa406b8c35b021d54d4fdada7b
9ce5d4ba5b06719e72aaf58c5aae7aca

y[2] 057aa0e2e74e7dcfd17a0823429db629

y[3]	65b7d563c57b4cec942cc865e29c1dad 83cac8b4d61aacc457f336e6a10b6632 3f5887bf3523dfcadee158503bfaa89d
y[4]	c6bf59daa82afd2b5ebb2a9ca6572a60 67cee7c327e9039b3b6ea6aledc7fdc3
y[5]	df927aade10c1c9f2d5ff446450d2a39 98d0f9f6202b5e07c3f97d2458c69d3c
y[6]	8190643978d7a7f4d64e97e3f1c4a08a 7c5bc03fd55682c017e2907eab07e5bb
y[7]	2f190143475a6043d5e6d5263471f4ee cf6e2575fbc6ff37edfa249d6cda1a09
y[8]	f797fd5a3cd53a066700f45863f04b6c 8a58cfd341241e002d0d2c0217472bf1
y[9]	8b636ae547c1771368d9f317835c9b0e f430b3df4034f6af00d0da44f4af7800
y[10]	bc7a5cf8a5abdb12dc718b559b74cab9 090e33cc58a955300981c420c4da8ffd
y[11]	67df540890a062fe40dba8b2c1c548ce d22473219c534911d48ccaabfb71bc71
y[12]	862f4a24ebd376d288fd4e6fb06ed870

y[13]	5787c5fedc813cd2697e5b1aac1ced45 767b14ce88409eaebb601a93559aae89 3e143d1c395bc326da821d79a9ed41dc
y[14]	fbe549147f71c092f4f3ac522b5cc572 90706650487bae9bb5671ecc9ccc2ce5
y[15]	lead87ac01985268521222fb9057df7e d41810b5ef0d4f7cc67368c90f573b1a
y[16]	c2ce956c365ed38e893ce7b2fae15d36 85a3df2fa3d4cc098fa57dd60d2c9754
y[17]	a8ade980ad0f93f6787075c3f680a2ba 1936a8c61d1af52ab7e21f416be09d2a
y[18]	8d64c3d3d8582968c2839902229f85ae e297e717c094c8df4a23bb5db658dd37
y[19]	7bf0f4ff3ffd8fba5e383a48574802ed 545bbe7a6b4753533353d73706067640
y[20]	135a7ce517279cd683039747d218647c 86e097b0daa2872d54b8f3e508598762
y[21]	9547b830d8118161b65079fe7bc59a99 e9c3c7380e3e70b7138fe5d9be255150
y[22]	2b698d09ae193972f27d40f38dea264a 0126e637d74ae4c92a6249fa103436d3

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y[23]      eb0d4029ac712bfc7a5eacbdd7518d6d
           4fe903a5ae65527cd65bb0d4e9925ca2
y[24]      4fd7214dc617c150544e423f450c99ce
           51ac8005d33acd74f1bed3b17b7266a4
y[25]      a3bb86da7eba80b101e15cb79de9a207
           852cf91249ef480619ff2af8cabca831
y[26]      25d1faa94cbb0a03a906f683b3f47a97
           c871fd513e510a7a25f283b196075778
y[27]      496152a91c2bf9da76ebe089f4654877
           f2d586ae7149c406e663eadeb2b5c7e8
y[28]      2429b9e8cb4834c83464f079995332e4
           b3c8f5a72bb4b8c6f74b0d45dc6c1f79
y[29]      952c0b7420df525e37c15377b5f09843
           19c3993921e5ccd97e097592064530d3
y[30]      3de3afad5733cbe7703c5296263f7734
           2efbf5a04755b0b3c997c4328463e84c
y[31]      aa2de3ffdc297baaaacd7ae646e44b5
           c0f16044df38fabd296a47b3a838a913
y[32]      982fb2e370c078edb042c84db34ce36b
           46ccb76460a690cc86c302457dd1cde1
y[33]      97ec8075e82b393d542075134e2a17ee
           70a5e187075d03ae3c853cff60729ba4
-----
LMS type   00000005                               # LM_SHA256_M32_H5
path[0]    4de1f6965bdabc676c5a4dc7c35f97f8
           2cb0e31c68d04f1dad96314ff09e6b3d
path[1]    e96ae300d1f68bf1bca9fc58e40323

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path[2]    36cd819aaf578744e50d1357a0e42867
           04d341aa0a337b19fe4bc43c2e79964d
           4f351089f2e0e41c7c43ae0d49e7f404
path[3]    b0f75be80ea3af098c9752420a8ac0ea
           2bbb1f4eeba05238aef0d8ce63f0c6e5
path[4]    e4041d95398a6f7f3e0ee97cc1591849
           d4ed236338b147abde9f51ef9fd4e1c1

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