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Standard

ISO/IEC 14888-4

**Information security — Digital
signatures with appendix —**

**Part 4:
Stateful hash-based mechanisms**

*Sécurité de l'information — Signatures digitales avec
appendice —*

Partie 4: Mécanismes basés sur le hachage dynamique

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Foreword

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A list of all parts in the ISO/IEC 14888 series can be found on the ISO and IEC websites.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html and www.iec.ch/national-committees.

Introduction

Digital signatures with appendix are designed to offer integrity, authentication and non-repudiation. ISO/IEC 14888-2 specifies the class of digital signature mechanisms in which the security is based on the difficulty of integer factorization. ISO/IEC 14888-3 specifies the class in which the security is based on computing discrete logarithms. Unfortunately, if and when a large-scale general purpose quantum computer becomes available, all of these techniques will no longer be secure for practical key sizes.^[1]

This document specifies a class of digital signatures whose security depends only on the security of the underlying hash function. At the time of publication of this document, standardized hash functions are believed to be secure even against attacks using large scale quantum computers. Hence, the schemes specified in this document do not suffer from the same problems as the schemes specified in ISO/IEC 14888-2 and ISO/IEC 14888-3.

The hash-based signature (HBS) schemes specified in this document are stateful schemes, whereby the private key is part of the state of the scheme. This means that at every signature generation, state information held by the signer must be updated, as otherwise the security of the scheme is compromised. Therefore, when deploying any of the schemes specified in this document, it is expected that robust state-management practices are implemented to ensure that state information is correctly updated.

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Information security — Digital signatures with appendix —

Part 4: Stateful hash-based mechanisms

1 Scope

This document specifies stateful digital signature mechanisms with appendix, where the level of security is determined by the security properties of the underlying hash function.

This document also provides requirements for implementing basic state management, which is needed for the secure deployment of the stateful schemes described in this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 authentication path

list of hash values that show that a specific node belongs to a *Merkle tree* (3.5)

3.2 balanced binary tree

ordered tree in which each node has exactly two other nodes that are directly subordinate

3.3 binary tree

ordered tree in which each node has at most two other nodes that are directly subordinate

[SOURCE: ISO/IEC-2382:2015, 2121636, modified — notes to entry have been removed.]

3.4 L-tree

unbalanced *binary tree* (3.3) used to compress the Winternitz+ One-Time Signature Scheme (WOTS+) public keys in the eXtended Merkle Signature Scheme (XMSS)

3.5 Merkle tree

balanced binary tree (3.2), where each node of the tree corresponds to the hash of the labels of the child nodes

3.6 one-time signature

digital signature scheme where the security is limited to signing a single message for a given key pair

3.7

**state
state information**

information regarding key usage stored with an eXtended Merkle Signature Scheme (XMSS) or Leighton-Micali signature scheme (LMS) private key

3.8

state management

processes by which the *state* (3.7) is updated with each signature

Note 1 to entry: This is a crucial part of any stateful hash-based signature, as incorrect state information can lead to signature forgeries.

3.9

Winternitz parameter

parameter in the Winternitz *one-time signature* (3.6) scheme, which allows a trade-off between signature size and computation time

4 Symbols and abbreviated terms

4.1 Symbols

$0x00$	the hexadecimal representation of the 0 byte
$a b$	concatenation of the bit sequences a and b in the order specified
$a * b$	multiplication of a and b
$a \& b$	bitwise logical AND of two bit strings a and b
$a \text{ XOR } b$	bitwise logical EXCLUSIVE OR of two bit strings a and b
$a \text{ mod } b$	the remainder when a is divided by b
$a \ll x$	the result of left-shifting a bit-string a by x positions (e.g. $0x08 \ll 1 = 0x10$)
$a \gg x$	the result of right-shifting a bit-string a by x positions (e.g. $0x08 \gg 1 = 0x04$)
$\text{ceil}(x)$	the least integer greater than or equal to x
d	the number of layers of sub-trees in XMSS-MT
$\text{floor}(x)$	the greatest integer less than or equal to x
h	total height of the Merkle tree (or hyper tree for XMSS-MT and HSS) NOTE 1 h is the parameter which controls the maximum number of signatures, which are given by 2^h .
$\text{lb}(x)$	the base 2 logarithm of x
n	the length in bytes of one element of the private key, public key or signature, and the length of the message representative
m	the arbitrary length message to be signed in XMSS, XMSS-MT, LM-OTS, LMS, and HSS
M'	the message representative signed in XMSS and XMSS-MT
$\text{toByte}(x,y)$	computation of the y -byte string containing the binary representation of x in big-endian byte order

w	the Winternitz parameter used in the XMSS and XMSS-MT algorithms
	NOTE 2 w controls the trade-off between computation time and signature size. Smaller values of w/W lead to faster computations, while larger values of w lead to smaller signatures.
W	the Winternitz parameter used in the LMS and HSS algorithms. W and w are related as follows: $w = 2^W$.
$x[i]$	the i th element of the array x
$[X]_y$	the result of truncating X to its leftmost y bits, e.g. $[0_{\text{xfe}}]_4 = 0_{\text{xf}}$

4.2 Abbreviated terms

HBS	hash-based signature
HSS	hierarchical signature scheme
LMS	Leighton-Micali signature scheme
OTS	one-time signature
RBG	random bit generator
WOTS+	Winternitz+ One-Time signature scheme
XMSS	eXtended Merkle Signature Scheme
XMSS-MT	eXtended Merkle Signature Scheme Multi Tree

5 XMSS and XMSS-MT

5.1 General

The XMSS scheme is a stateful hash-based signature scheme for which only a limited number of signatures can be created using a particular private key. The security of XMSS is based on the hardness of the Target Collision Resistance (TCR) problem, and XMSS has been proven to be secure in the standard model (see Reference [13]).

The XMSS-MT scheme, a variant of the XMSS scheme, is a stateful hash-based signature scheme that supports a larger number of signatures than XMSS. XMSS-MT inherits all the security properties of XMSS.[14]

The OIDs for these algorithms shall be in accordance with [Annex A](#). Test vectors can be found in [Annex C](#).

5.2 Common building blocks

5.2.1 General

The XMSS and the XMSS-MT schemes are described in a unified way since they employ common building blocks.

5.2.2 Address format

The *ADRS* input has three different address formats (see [Table 1](#)). Each layout is appropriate for a different step of the algorithms:

- the OTS address format is for the hash calls in the one-time signature schemes;
- the L-tree address format is for hashes used in the L-trees;

— the hash tree address format is for the Merkle-tree construction.

An L-tree is an unbalanced binary hash tree used to compute the leaves of the main XMSS binary hash tree.

Each *ADRS* address format consists of six 32-bit fields and one 64-bit field. The fields are encoded as unsigned integers. The *layerAddress* field refers to the layer in a multi-tree construction (0 if not using multi-trees). The *treeAddress* refers to the position (from left to right) of a tree in a multi-tree construction (0 if not using multi-trees). The *field* type differentiates the three *ADRS* layouts: 0 for OTS, 1 for L-tree and 2 for Hash tree. The field *keyAndMask* is used to distinguish if the hash call intends to generate a key (0) or a bitmask (1) for an OTS address. In the case of the L-tree and Hash tree address, *keyAndMask* is: (0) to generate a key, (1) to generate the most significant *n* bytes of the *2n*-byte bitmask and (2) to generate the least significant *n* bytes of the *2n*-byte bitmask.

Table 1 — XMSS address formats

OTS address	L-tree address	Hash tree address
+-----+ layerAddress (32 bits) +-----+	+-----+ layerAddress (32 bits) +-----+	+-----+ layerAddress (32 bits) +-----+
+-----+ treeAddress (64 bits) +-----+	+-----+ treeAddress (64 bits) +-----+	+-----+ treeAddress (64 bits) +-----+
+-----+ type = 0 (32 bits) +-----+	+-----+ type = 1 (32 bits) +-----+	+-----+ type = 2 (32 bits) +-----+
+-----+ OTSAddress (32 bits) +-----+	+-----+ ltreeAddress (32 bits) +-----+	+-----+ padding = 0 (32 bits) +-----+
+-----+ chainAddress (32 bits) +-----+	+-----+ treeHeight (32 bits) +-----+	+-----+ treeHeight (32 bits) +-----+
+-----+ hashAddress (32 bits) +-----+	+-----+ treeIndex (32 bits) +-----+	+-----+ treeIndex (32 bits) +-----+
+-----+ keyAndMask (32 bits) +-----+	+-----+ keyAndMask (32 bits) +-----+	+-----+ keyAndMask (32 bits) +-----+

NOTE Each XMSS Address in this table is 32-bytes.

The field *OTSAddress* encodes the index of the OTS key pair within the tree, the *chainAddress* encodes the chain index and finally the *hashAddress* encodes the hash function call index within the chain.

In the L-tree address layout, the *ltreeAddress* field encodes the index of the leaf computed with this L-tree. The *treeHeight* encodes the height of the node used as input for the next computation inside the L-tree. The *treeIndex* encodes the index of the node at that height, inside the L-tree.

In the tree hash address format, the *padding* field is always 0. The *treeHeight* encodes the height of the tree node being used for the next computation, followed by the *treeIndex* which is the node index at that height. For the L-tree address layout, the *keyAndMask* field can be: 0 (key), 1 (first bitmask), and 2 (second bitmask).

5.2.3 Required cryptographic functions

5.2.3.1 General

The XMSS scheme uses the following cryptographic primitives:

- Keyed Hash-Function $F(KEY, M)$, where *KEY* is an *n*-byte key, *M* is an *n*-byte message and the output is *n* bytes.
- Keyed Hash-Function $H(KEY, M)$, where *KEY* is an *n*-byte key, *M* is a *2n*-byte message and the output is *n* bytes.
- Keyed Hash-Function $H_msg(KEY, M)$, where *KEY* is a *3n*-byte key, *M* is an arbitrary length message and the output is *n* bytes.
- Pseudo-Random Function $PRF(KEY, M)$, where *KEY* is an *n*-byte key, *M* is a 32-byte message and the output is *n* bytes.

- Pseudo-Random Function $\text{PRF}_{\text{Keygen}}(\text{KEY}, M)$, where KEY is an n -byte key, M is a 32-byte message and the output is n bytes. This function is optional and only used if WOTS+ private keys are generated pseudo-randomly.
- Pseudo-Random Function $\text{PRF}_{\text{Keygen_MT}}(\text{KEY}, M)$, where KEY is an n -byte key, M is a 32-byte message and the output is n bytes. This function is only used in XMSS_keygen if called from XMSS_MT_keygen .
- A non-deterministic random number generator RBG that provides at least a security level of $8n$ bits.

These functions shall be implemented with SHA2-256 (Dedicated Hash-Function 4 defined in ISO/IEC 10118-3), SHAKE256 (see ISO/IEC 10118-3:2018, C.2) as described below (see [Annex B](#) for further considerations on these instantiations).

5.2.3.2 Functions Based on SHA2-256

When using SHA2-256 as the underlying hash function and $n=32$, the following constructions shall be used.

- $F(\text{KEY}, M)$: $\text{SHA2-256}(\text{toByte}(0, 32) \parallel \text{KEY} \parallel M)$
- $H(\text{KEY}, M)$: $\text{SHA2-256}(\text{toByte}(1, 32) \parallel \text{KEY} \parallel M)$
- $H_{\text{msg}}(\text{KEY}, M)$: $\text{SHA2-256}(\text{toByte}(2, 32) \parallel \text{KEY} \parallel M)$
- $\text{PRF}(\text{KEY}, M)$: $\text{SHA2-256}(\text{toByte}(3, 32) \parallel \text{KEY} \parallel M)$
- $\text{PRF}_{\text{Keygen}}(\text{KEY}, M)$: $\text{SHA2-256}(\text{toByte}(4, 32) \parallel \text{KEY} \parallel M)$
- $\text{PRF}_{\text{Keygen_MT}}(\text{KEY}, M)$: $\text{SHA2-256}(\text{toByte}(5, 32) \parallel \text{KEY} \parallel M)$

When using SHA2-256 as the underlying hash function and $n=24$, the following constructions shall be used.

- $F(\text{KEY}, M)$: $\text{SHA2-256/192}(\text{toByte}(0, 4) \parallel \text{KEY} \parallel M)$
- $H(\text{KEY}, M)$: $\text{SHA2-256/192}(\text{toByte}(1, 4) \parallel \text{KEY} \parallel M)$
- $H_{\text{msg}}(\text{KEY}, M)$: $\text{SHA2-256/192}(\text{toByte}(2, 4) \parallel \text{KEY} \parallel M)$
- $\text{PRF}(\text{KEY}, M)$: $\text{SHA2-256/192}(\text{toByte}(3, 4) \parallel \text{KEY} \parallel M)$
- $\text{PRF}_{\text{Keygen}}(\text{KEY}, M)$: $\text{SHA2-256/192}(\text{toByte}(4, 4) \parallel \text{KEY} \parallel M)$
- $\text{PRF}_{\text{Keygen_MT}}(\text{KEY}, M)$: $\text{SHA2-256/192}(\text{toByte}(5, 4) \parallel \text{KEY} \parallel M)$

5.2.3.3 Functions Based on SHAKE

When using SHAKE256 and $n=32$, the following constructions shall be used.

- $F(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(0, 32) \parallel \text{KEY} \parallel M, 256)$
- $H(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(1, 32) \parallel \text{KEY} \parallel M, 256)$
- $H_{\text{msg}}(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(2, 32) \parallel \text{KEY} \parallel M, 256)$
- $\text{PRF}(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(3, 32) \parallel \text{KEY} \parallel M, 256)$
- $\text{PRF}_{\text{Keygen}}(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(4, 32) \parallel \text{KEY} \parallel M, 256)$
- $\text{PRF}_{\text{Keygen_MT}}(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(5, 32) \parallel \text{KEY} \parallel M, 256)$

When using SHAKE256 and $n=24$, the following constructions shall be used.

- $F(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(0, 4) \parallel \text{KEY} \parallel M, 192)$
- $H(\text{KEY}, M)$: $\text{SHAKE256}(\text{toByte}(1, 4) \parallel \text{KEY} \parallel M, 192)$

- $H_msg(KEY, M)$: SHAKE256(toByte(2, 4) || KEY || M , 192)
- $PRF(KEY, M)$: SHAKE256(toByte(3, 4) || KEY || M , 192)
- $PRF_{Keygen}(KEY, M)$: SHAKE256(toByte(4, 4) || KEY || M , 192)
- $PRF_{Keygen_MT}(KEY, M)$: SHAKE256(toByte(5, 4) || KEY || M , 192)

5.2.4 Auxiliary functions

5.2.4.1 General

Both XMSS and XMSS-MT make use of two auxiliary functions, namely the `base_w` function and the chain function. The specifications of these auxiliary functions are given in [5.2.4.2](#) and [5.2.4.3](#).

5.2.4.2 `base_w` auxiliary function

This function is used in the signing and verification process to convert a string of bytes into a sequence of base w integers (i.e. integers between 0 and $w-1$).

Algorithm: `base_w(X, w, out_len)`.

Input: A sequence of bytes $X = X[0], \dots, X[*len_x* - 1]$ of length len_x , the base w which shall be 4 or 16, and the output length out_len .

Output: A sequence of integers $Q = Q[0], \dots, Q[*out_len* - 1]$ of length out_len from the set $\{0, 1, \dots, w-1\}$

Steps:

- a) Set $in = 0, out = 0, total = 0, bits = 0$.
- b) For i from 0 to $out_len - 1$:
 - 1) If $bits$ is equal to 0 then
 - i) Set $total = X[in]$.
 - ii) Set $in = in + 1$.
 - iii) Set $bits = 8$.
 - 2) Set $bits = bits - \text{lb}(w)$.
 - 3) Set $Q[out] = (total \gg bits) \& (w - 1)$.
 - 4) Set $out = out + 1$.
- c) Return Q .

5.2.4.3 Chain auxiliary function

The chain function is the main building block of the XMSS and XMSS-MT schemes. This is the function used multiple times to produce the public key and signature from the private key material.

Algorithm: `chain($X, i, s, SEED, ADRS$)`.

Input: A string X , starting index i , length s of the hash chain to be computed, n -byte value $SEED$, 32-byte value $ADRS$ formatted as an OTS address according to [Table 1](#).

Output: An n -byte value output

Steps:

- a) If s is equal to 0, then return X .
- b) If $(i + s) > w - 1$, then return $NULL$.
- c) Set $tmp = \text{chain}(X, i, s - 1, SEED, ADRS)$.
- d) Set $ADRS.hashAddress = (i + s - 1)$.
- e) Set $ADRS.keyAndMask = 0$.
- f) Set $KEY = \text{PRF}(SEED, ADRS)$.
- g) Set $ADRS.keyAndMask = 1$.
- h) Set $BM = \text{PRF}(SEED, ADRS)$.
- i) Return $F(KEY, tmp \text{ XOR } BM)$.

5.2.5 WOTS+ One-Time Signature Auxiliary Scheme

5.2.5.1 General

Both XMSS and XMSS-MT make use of an underlying one-time signature scheme called WOTS+. A one-time signature scheme has limited applicability because a signing key can only be used to sign a single message. If the same one-time signing key is used twice, the scheme loses its security guarantees (in particular, signature forgery becomes possible). WOTS+ shall not be used outside the context of XMSS and XMSS-MT. [5.2.5.2](#) gives the definition of WOTS+ key generation, signing and verification, which are algorithms used by XMSS/XMSS-MT key generation, signing and verification, respectively.

5.2.5.2 WOTS+ key generation

5.2.5.2.1 General

[5.2.5.2.2](#), [5.2.5.2.3](#) and [5.2.5.2.4](#) describe the key generation process for WOTS+. There are two possible methods to create the private key: 1) generate the private key from a single seed ([5.2.5.2.2](#)), and 2) generate a uniform random private key ([5.2.5.2.3](#)). The main difference is that the method described in [5.2.5.2.2](#) is more memory-efficient as it uses a pseudo-random function to generate all WOTS+ private key elements from a single seed, while the one described in [5.2.5.2.3](#) does not introduce an additional security assumption regarding the pseudo-random function step.

Throughout the document, various other algorithms are required to generate WOTS+ private keys. For those, it is always assumed that the pseudo-random method described in [5.2.5.2.2](#) is used. Trivial changes (omitted for simplicity) to these algorithms are allowed so that the method described in [5.2.5.2.3](#) is used instead, at the cost of storing all WOTS+ private keys. The public key generation given in [5.2.5.2.4](#) is the same for both private key generation methods.

5.2.5.2.2 WOTS+ Private Key (pseudo-random)

This algorithm generates a WOTS+ private key. This method is called by the XMSS and XMSS-MT signatures schemes and makes use of SK_S , which works as a seed for the generation of all WOTS+ private keys. This method also receives an index idx which specifies what WOTS+ private key is required to be generated (among the 2^h possible ones), and the layer L and tree address T to identify the XMSS sub-tree (relevant when using the XMSS-MT variant).

Algorithm: $\text{WOTS+_generate_privkey}(SK_S, SEED, idx, L, T)$.

Input: An n -byte string SK_S , public seed $SEED$, an integer idx , layer L , tree address T .

Output: A sequence of n -byte values sk of length len .

Steps:

- a) Set $ADRS = \text{toByte}(0, 32)$.
- b) Set $ADRS.\text{layerAddress} = L$.
- c) Set $ADRS.\text{treeAddress} = T$.
- d) Set $ADRS.\text{OTSAddress} = \text{idx}$.
- e) Set $ADRS.\text{hashAddress} = 0$.
- f) For i from 0 to $len - 1$:
 - 1) Set $ADRS.\text{chainAddress} = i$.
 - 2) Set $sk[i] = \text{PRF}_{\text{Keygen}}(SK_S, SEED || ADRS)$
- g) Return sk .

5.2.5.2.3 WOTS+ private key (random)

This algorithm generates a WOTS+ private key.

Algorithm: $\text{WOTS+}_\text{generate_privkey_random}()$.

Input: None.

Output: A sequence of n -byte values sk of length len .

Steps:

- a) For i from 0 to $len - 1$:
 - 1) Let $sk[i]$ be an n -byte string from the output generation function of an RBG
- b) Return sk .

5.2.5.2.4 WOTS+ public key

This algorithm generates a WOTS+ public key from a private key. It should be noted that the $SEED$ used here is public information that is also made available to the verifier.

Algorithm: $\text{WOTS+}_\text{generate_pubkey}(sk, SEED, ADRS)$.

Input: Sequence of n -byte strings sk of length len , n -byte $SEED$, a 32-byte $ADRS$ formatted as an OTS address according to [Table 1](#).

Output: Sequence of n -byte strings pk of length len .

Steps:

- a) For i from 0 to $len - 1$:
 - 1) Set $ADRS.\text{chainAddress} = i$.
 - 2) Set $pk[i] = \text{chain}(sk[i], 0, w - 1, SEED, ADRS)$.
- b) Return pk .

5.2.5.3 WOTS+ signing

This algorithm generates a signature from a private key and a message. The values len_1 and len_2 used in WOTS+_sign are constants derived from the parameters n and w :

- $len_1 = \text{ceil}(8*n/\text{lb}(w))$
- $len_2 = \text{floor}(\text{lb}(len_1 * (w - 1)) / \text{lb}(w)) + 1$

Algorithm: WOTS+_sign($sk, m, SEED, ADRS$).

Input: A private key SK , a message M' of length n bytes to be signed, n -byte $SEED$, a 32-byte $ADRS$ formatted as an OTS address according to [Table 1](#).

Output: Signature sig for the message M' .

Steps:

- a) Set $csum = 0$.
- b) Set $msg = \text{base}_w(M', w, len_1)$.
- c) For i from 0 to $len_1 - 1$:
 - 1) Set $csum = csum + w - 1 - msg[i]$.
- d) Set $csum = csum \ll (8 - ((len_2 * \text{lb}(w)) \bmod 8))$.
- e) Set $len2_bytes = \text{ceil}((len_2 * \text{lb}(w)) / 8)$.
- f) Set $msg = msg || \text{base}_w(\text{toByte}(csum, len2_bytes), w, len_2)$.
- g) For i from 0 to $len - 1$:
 - 1) Set $ADRS.chainAddress = i$.
 - 2) Set $sig[i] = \text{chain}(SK[i], 0, msg[i], SEED, ADRS)$.
- h) Return sig .

5.2.5.4 WOTS+ verification

5.2.5.4.1 Compute the WOTS+ public key

This algorithm verifies if a signature is authentic given a signature, a public key and a message. The WOTS+ verification process is divided into two parts. The first one recomputes the WOTS+ public key from the WOTS+ signature. The second one checks if the recomputed WOTS+ public key matches the original one.

When used in the context of XMSS or XMSS-MT signature verification, only the first part of the WOTS+ verification process is performed, i.e. the WOTS+ public key recovery step. It is never compared with any other WOTS+ public key. This verification is implicitly done at the XMSS or XMSS-MT signature verification level.

This algorithm computes a WOTS+ public key from a message and its signature.

Algorithm: WOTS+_pk_from_sig($sig, M', SEED, ADRS$).

Input: A signature sig , a message M' of length n bytes, n -byte $SEED$, a 32-byte $ADRS$ formatted as an OTS address according to [Table 1](#).

Output: A public key candidate tmp_pk .

Steps:

- a) Set $csum = 0$.

- b) Set $msg = \text{base}_w(M', w, len_1)$.
- c) For i from 0 to $len_1 - 1$:
 - 1) Set $csum = csum + w - 1 - msg[i]$.
- d) Set $csum = csum \ll (8 - ((len_2 * \text{lb}(w)) \bmod 8))$.
- e) Set $len2_bytes = \text{ceil}((len_2 * \text{lb}(w)) / 8)$.
- f) Set $msg = msg \parallel \text{base}_w(\text{toByte}(csum, len2_bytes), w, len_2)$.
- g) For i from 0 to $len - 1$:
 - 1) Set $ADRS.chainAddress = i$.
 - 2) Set $tmp_pk[i] = \text{chain}(sig[i], msg[i], w - 1 - msg[i], SEED, ADRS)$.
- h) Return tmp_pk .

5.3 XMSS Algorithms

5.3.1 General

The XMSS scheme is a multi-time stateful signature scheme that allows for a large but fixed number of signatures. It uses the WOTS+ one-time signature scheme as a building block. It also uses a perfectly balanced binary tree, called a Merkle tree. This binary tree has height h/d (for XMSS, $d = 1$ and therefore $h/d = h$, while for XMSS-MT $d > 1$). For the sake of simplicity, the height can be considered to be h , since this refers to XMSS specifically. A tree of height h has exactly 2^h leaf nodes. Each leaf node represents one WOTS+ key pair that can be used to generate one signature. In practice, such a binary tree represents a set of 2^h WOTS+ key pairs, thus an XMSS instantiation with parameter h allows up to 2^h signatures.

To prevent reusing the same WOTS+ key pair, each leaf node (which is associated with a WOTS+ key pair) is numbered from 0 to $(2^h - 1)$, where the leftmost leaf node has index 0. After producing a new WOTS+ signature, the index shall be increased by 1. This process shall be flawlessly performed since reusing the same WOTS+ key pair more than once voids its security guarantees. This process makes the XMSS scheme a stateful scheme, meaning that the signer shall flawlessly update this index after each signature.

An XMSS signature essentially consists of two things: a WOTS+ signature and the authentication path, which is a set of nodes of the Merkle tree. The WOTS+ signature is used to re-generate the WOTS+ public key associated with the current leaf node. The WOTS+ public key plus the authentication path are enough information for a verifier to reconstruct the root of the Merkle tree. If the re-computed root node matches with the XMSS public key, the verifier then knows that the signature is authentic.

There are several methods to compute authentication paths, and each one offers a different performance profile, although all of them should compute exactly the same authentication path for a given signature.

The key generation and signing algorithms (for both XMSS and XMSS-MT) assume that the pseudo-random WOTS+ private key generation method described in [5.2.5.2.2](#) is used. In this case, the WOTS+ private keys are generated from a seed SK_S contained in the private key SK . If the random method described in [5.2.5.2.3](#) is used instead, the XMSS private key will not have a SK_S element, but rather the WOTS+ private keys instead.

5.3.2 Auxiliary functions

5.3.2.1 RAND_HASH

This algorithm implements the randomized tree hashing.

Algorithm: $\text{RAND_HASH}(LEFT, RIGHT, SEED, ADRS)$.

Input: An n -byte string $LEFT$, an n -byte string $RIGHT$, an n -byte string $SEED$, a 32-byte string $ADRS$ formatted according to [Table 1](#) as either an L-tree Address or a Hash tree Address.

Output: An n -byte string.

Steps:

- a) Set $ADRS.keyAndMask = 0$.
- b) Set $KEY = PRF(SEED, ADRS)$.
- c) Set $ADRS.keyAndMask = 1$.
- d) Set $BM_0 = PRF(SEED, ADRS)$.
- e) Set $ADRS.keyAndMask = 2$.
- f) Set $BM_1 = PRF(SEED, ADRS)$.
- g) Return $H(KEY, (LEFT \text{ XOR } BM_0) || (RIGHT \text{ XOR } BM_1))$.

5.3.2.2 L_TREE

This algorithm compresses a WOTS+ public key pk into a single n -byte value $pk[0]$.

Algorithm: $L_TREE(pk, SEED, ADRS)$.

Input: A sequence of n -byte strings pk of length len , public $SEED$, and 32-byte address $ADRS$ formatted according to [Table 1](#) as an L-tree Address. It should be noted that this method modifies the input pk .

Output: An n -byte string $pk[0]$.

Steps:

- a) Set $len' = len$.
- b) Set $ADRS.treeHeight = 0$.
- c) While $len' > 1$ do:
 - 1) For i from 0 to $\text{floor}(len'/2) - 1$:
 - i) Set $ADRS.treeIndex = i$.
 - ii) Set $pk[i] = RAND_HASH(pk[2i], pk[2i + 1], SEED, ADRS)$.
 - 2) If $len' \bmod 2$ is equal to 1:
- d) Set $pk[\text{floor}(len'/2)] = pk[len' - 1]$.
 - 1) Set $len' = \text{ceil}(len'/2)$.
 - 2) Increment $ADRS.treeHeight$ by 1.
- e) Return $pk[0]$.

5.3.2.3 treeHash

The $treeHash$ algorithm is an auxiliary function that computes a specific node of the tree. It is used in the context of generating key pairs and computing authentication paths. It makes use of the conventional stack data structure which has a push (insert an item at the top of the stack) and a pop (remove an item from the top of the stack) operation working in a last-in-first-out fashion.

Algorithm: $treeHash(SK, s, t, ADRS)$.

ISO/IEC 14888-4:2024(en)

Input: XMSS private key SK , an unsigned integer s representing the start index, an unsigned integer t representing the target node height, and an address $ADRS$ formatted according to [Table 1](#) as a Hash tree Address.

Output: n -byte root node of a sub-tree.

Steps:

- a) If $(s \bmod (2^t))$ is not equal to 0) return -1.
- b) for i from 0 to $2^t - 1$:
 - 1) Set $SEED = SK.SEED$.
 - 2) Set $ADRS.type = 0$.
 - 3) Set $ADRS.OTSAddress = (s + i)$.
 - 4) Set $pk = WOTS+_generate_pubkey(WOTS+_generate_privkey(SK.SK_S, SEED, s + i, ADRS.layerAddress, ADRS.treeAddress), SEED, ADRS)$.
 - 5) Set $ADRS.type = 1$
 - 6) Set $ADRS.ltreeAddress = (s + i)$.
 - 7) Set $node = L_TREE(pk, SEED, ADRS)$.
 - 8) Set $ADRS.type = 2$.
 - 9) Set $ADRS.padding = 0$.
 - 10) Set $ADRS.treeHeight = 0$.
 - 11) Set $ADRS.treeIndex = (i + s)$.
 - 12) While ($Stack$ is not empty and Top node on $Stack$ has same height t' as $node$):
 - i) Set $ADRS.treeIndex = ((ADRS.treeIndex - 1) / 2)$.
 - ii) Set $node = RAND_HASH(Stack.pop(), node, SEED, ADRS)$.
 - iii) Set $ADRS.treeHeight = (ADRS.treeHeight + 1)$.
 - 13) $Stack.push(node)$.
- c) Return $Stack.pop()$.

The description above assumes that the pseudo-random key generation method from [5.2.5.2.2](#) is used. Alternatively, if the method from [5.2.5.2.3](#) is used, then step b)4) would not reconstruct the private key, and instead it would use the one stored in sk (i.e. the WOTS+ private key).

5.3.3 XMSS Key Generation

5.3.3.1 General

This key generates an XMSS key pair for a given layer and tree. The XMSS private and public key generation methods described in [5.3.3.2](#) follow the definition provided in Section 7.2.1 of NIST SP 800-208.^[12] The XMSS private and public keys consist of the following components:

NOTE $SEED$ and $root$ are public and stored in private and public keys.

— Private key:

- If the pseudo-random method described in [5.2.5.2.2](#) is used, a seed SK_S (n bytes),

- If the random method described in [5.2.5.2.3](#) is used, 2^h WOTS+ private keys ($2^h * len * n$ bytes),
- *SK_PRF*, a key for the PRF (n bytes),
- *idx*, index of the next WOTS+ private key that has not been used yet (8 bytes),
- *root*, the root of the tree (n bytes),
- *SEED*, the public seed (n bytes);
- Public key:
 - *type*, the type code (4 bytes),
 - *root*, the root of the tree (n bytes),
 - *SEED*, the public seed (n bytes).

The XMSS_keygen algorithm also helps with the computation of the authentication path for the first signature. The *type* code, which uniquely identifies the algorithm and parameter configuration, which is returned as part of the public key, is assumed to be known by the implementation (as all other cipher parameters).

The XMSS key generation is given in two flavours: one that shall be used if XMSS is used isolated, and another one that shall be used if integrated into XMSS-MT key generation procedure. It is possible to implement both flavours as a single algorithm but this would lead to if-then-else branches and optional parameters. For the sake of clarity, they are presented separately.

Both methods assume that the pseudo-random WOTS+ private key generation method described in [5.2.5.2.2](#) is used, which derives all WOTS+ private key elements from *SK_S*. If the random method described in [5.2.5.2.3](#) is used, instead then the XMSS private key shall not have a *SK_S* element, and the XMSS private key shall store all ($2^{h/d}$ in total) WOTS+ private keys instead.

5.3.3.2 XMSS Key Generation (For XMSS-only)

Algorithm: XMSS_keygen()

Output: private key *SK*, public key *PK*.

Steps:

- a) Let *SK.SK_S* be an n -byte string from the output generation function of an RBG.
- b) Let *SK.SEED* be an n -byte string from the output generation function of an RBG.
- c) Set *ADRS* = toByte(0, 32).
- d) Let *SK_PRF* be an n -byte string from the output generation function of an RBG.
- e) Set *root* = treeHash(*SK*, 0, h , *ADRS*).
- f) Set *SK.idx* = 0.
- g) Set *SK.root* = *root*.
- h) Set *SK* = *idx* || *SK_S* || *SK_PRF* || *root* || *SK.SEED*.
- i) Set *PK* = *type* || *root* || *SK.SEED*.
- j) Return (*SK* || *PK*).

5.3.3.3 XMSS Key Generation (For XMSS-MT integration)

Algorithm: XMSS_keygen(*SK_MTS_S*, L , T , *ADRS*).

Input: an n -byte string from the output generation function of an RBG called SK_MTS_S , the layer L (in the range $[0, \dots, d-1]$, where d is the number of layers for XMSS-MT), the tree index T , an n -byte $ADRS$.

Output: private key SK , public key PK .

Steps:

- a) Let $SK.SEED$ be an n -byte string from the output generation function of an RBG.
- b) Set $ADRS.layerAddress = L$.
- c) Set $ADRS.treeAddress = T$.
- d) Set $SK.SK_S = \text{PRF}_{\text{Keygen_MT}}(SK_MTS_S, SEED \parallel ADRS)$.
- e) Let SK_PRF be an n -byte string from the output generation function of an RBG.
- f) Set $root = \text{treeHash}(SK, 0, h/d, ADRS)$.
- g) Set $SK.idx = T * 2^{(h / d)}$.
- h) Set $SK.root = root$.
- i) Set $SK = idx \parallel SK_S \parallel SK_PRF \parallel root \parallel SK.SEED$.
- j) Set $PK = type \parallel root \parallel SK.SEED$.
- k) Return $(SK \parallel PK)$.

5.3.4 XMSS Signing

Given an XMSS private key, a message and an authentication path, this algorithm generates an XMSS signature and updates the XMSS private key. This algorithm assumes that the authentication path has already been pre-computed using one of the authentication path computation algorithms. A simple authentication path computation algorithm is given in 5.3.5. It should be noted that the XMSS signing algorithm modifies the XMSS private key given the index update process.

The XMSS signature consists of the following components.

- idx_sig , the index of the used WOTS+ key pair (8 bytes),
- r , a byte string used for randomized message hashing (n bytes),
- sig_ots , a WOTS+ signature ($len \cdot n$ bytes),
- $AUTH$, the authentication path for the leaf ($h \cdot n$ bytes).

Algorithm: $\text{XMSS_sign}(SK, AUTH, m)$.

Input: Private key SK , authentication path $AUTH$, message m .

Output: The updated private key SK and the signature Sig .

Steps:

- a) Set $idx_sig = SK.idx$.
- b) Set $SK.idx = SK.idx + 1$.
- c) Set $ADRS = \text{toByte}(0, 32)$.
- d) Set $r = \text{PRF}(SK.PRF, \text{toByte}(idx_sig, 32))$.
- e) Set $M' = \text{H_msg}(r \parallel SK.root \parallel \text{toByte}(idx_sig, n), m)$.

- f) Set $ADRS.type = 0$.
- g) Set $ADRS.OTSAddress = idx_sig$.
- h) Set $sig_ots = WOTS+_sign(WOTS+_generate_privkey(SK.SK_S, idx_sig, ADRS.layerAddress, ADRS.treeAddress), M', SK.SEED, ADRS)$.
- i) Set $Sig = idx_sig || r || sig_ots || AUTH$.
- j) Return (SK, Sig) .

In step b), SK shall be updated. No signature shall be returned if the update of SK fails.

5.3.5 XMSS Authentication Path Computation

This algorithm computes the authentication path given the XMSS private key SK , the WOTS+ key pair of index i , and $ADRS$. It is important to note that this algorithm is simple but not efficient. A more efficient variant called the BDS algorithm can be found in Reference [11]. Any authentication path algorithm, when correctly implemented, shall return the same authentication path for a given XMSS private key, WOTS+ key pair index and $ADRS$ buffer.

Algorithm: $buildAuth(SK, i, ADRS)$.

Input: the XMSS private key SK , the WOTS+ key pair index i , and $ADRS$ which is 32-byte value formatted according to Table 1.

Output: $AUTH$, the authentication path for key pair index i .

Steps:

- a) For j from 0 to $h/d - 1$:
 - 1) Set $k = \text{floor}(i / (2^j)) \text{ XOR } 1$.
 - 2) Set $AUTH[j] = \text{treeHash}(SK, k * 2^j, j, ADRS)$.
- b) Return $AUTH$.

5.3.6 XMSS Verification

5.3.6.1 General

The XMSS verification algorithm is divided into two procedures: the first computes a root node from the XMSS signature and the second one checks if the produced root node matches the XMSS public key root node. If they match, the signature is accepted as authentic, and rejected otherwise.

5.3.6.2 Compute Root Node from Signature

This algorithm computes a root node from a signature, a message, PK , and an n -byte $ADRS$.

Algorithm: $XMSS_rootFromSig(sig, M', PK, ADRS)$.

Input: Tree signature sig , n -byte $ADRS$ message M' , public key PK .

Output: The *root* node computed from the signature.

Steps:

- a) Set $sig_ots = sig.sig_ots$.
- b) Set $idx_sig = sig.idx_sig$.
- c) Set $AUTH = sig.auth$.

- d) Set $SEED = PK.SEED$.
- e) Set $ADRS.Type = 0$.
- f) Set $ADRS.OTSAddress = idx_sig$.
- g) Set $pk_ots = WOTS+_pk_from_sig(sig_ots, M', SEED, ADRS)$.
- h) Set $ADRS.Type = 1$.
- i) Set $ADRS.ltreeAddress = idx_sig$.
- j) Set $node[0] = L_TREE(pk_ots, SEED, ADRS)$.
- k) Set $ADRS.Type = 2$.
- l) Set $ADRS.Padding = 0$.
- m) Set $ADRS.TreeIndex = idx_sig$.
- n) For i from 0 to $h/d - 1$:
 - 1) Set $ADRS.TreeHeight = i$.
 - 2) If $\text{floor}(idx_sig / 2^i) \bmod 2$ is equal to 0:
 - i) Set $ADRS.Treeindex = ADRS.TreeIndex / 2$.
 - ii) Set $node[1] = \text{RAND_HASH}(node[0], AUTH[i], SEED, ADRS)$.
 - 3) If $\text{floor}(idx_sig / 2^i) \bmod 2$ is not equal to 0:
 - i) Set $ADRS.Treeindex = (ADRS.TreeIndex - 1) / 2$.
 - ii) Set $node[1] = \text{RAND_HASH}(AUTH[i], node[0], SEED, ADRS)$.
 - 4) Set $node[0] = node[1]$.
- o) Return $node[0]$.

5.3.6.3 XMSS Verify

This algorithm verifies an XMSS signature using the XMSS public key and a message.

Algorithm: $\text{XMSS_verify}(Sig, PK, m)$.

Input: Signature Sig , public key PK , message m .

Output: $VALID$ or $INVALID$.

Steps:

- a) Set $ADRS = \text{toByte}(0, 32)$.
- b) Set $M' = H_msg(r \parallel PK.root \parallel \text{toByte}(idx_sig, n), m)$;
- c) Set $node = \text{XMSS_rootFromSig}(Sig, M', PK, ADRS)$.
- d) If $node$ is equal to $PK.Root$, then return $VALID$.
- e) If $node$ is not equal to $PK.Root$, then return $INVALID$.

5.4 XMSS-MT Algorithms

5.4.1 General

The XMSS Multi-Tree (XMSS-MT) scheme is a variant of the XMSS scheme and allows for a very large number of signatures (e.g. 2^{60}). To achieve this, the Merkle tree used in XMSS-MT is composed of many sub-trees. Each sub-tree has a height h / d , and there are d layers of sub-trees. The parameter d is important for XMSS-MT, while it can be assumed as $d = 1$ for XMSS.

The type code, which uniquely identifies the algorithm and parameter configuration (returned as part of the public key), is assumed to be known by the implementation. This is also the case for all other cipher parameters).

5.4.2 XMSS-MT key Generation

This algorithm generates an XMSS-MT private and public key.

Algorithm: XMSS_MT_keygen().

Input: No input.

Output: An XMSS-MT key pair (SK_{MT}, PK_{MT}).

Steps:

- a) Set $SK_{MT}.idx_{MT} = 0$.
- b) Set $SK_{MT}.idx = 0$.
- c) Let $SK_{MT}.SK_S$ be an n -byte string from the output generation function of an RBG.
- d) Let $SK_{MT}.SK_{PRF}$ be an n -byte string from the output generation function of an RBG.
- e) Let $SK_{MT}.SEED$ be an n -byte string from the output generation function of an RBG.
- f) Set $ADRS = \text{toByte}(0, 32)$
- g) For *layer* from 0 to $d - 1$:
 - 1) Set $ADRS.layerAddress = layer$.
 - 2) For *tree* from 0 to $(1 \ll ((d - 1 - layer) * (h / d))) - 1$:
 - i) Set $ADRS.treeAddress = tree$.
 - ii) Set $(XMSS_SK, XMSS_PK) = XMSS_keygen(SK_{MT}.SK_S, tree, layer, ADRS)$
 - iii) set $XMSS_SK(SK_{MT}, XMSS_SK.SK_S, tree, layer)$.
- h) Set $XMSS_SK = \text{getXMSS_SK}(SK_{MT}, 0, d-1)$.
- i) Set $XMSS_SK.SEED = SK_{MT}.SEED$.
- j) Set $root = \text{treeHash}(XMSS_SK, 0, h / d, ADRS)$.
- k) Set $SK_{MT}.root = root$.
- l) Set $PK_{MT} = type || root || SEED$.
- m) Return $(SK_{MT} || PK_{MT})$.

$\text{setXMSS_SK}(SK_{MT}, SK_{MT}.SK_S, tree, layer)$ denotes the procedure that sets the private key for the specific XMSS subtree. $\text{getXMSS_SK}(SK_{MT}, tree, layer)$ denotes the procedure that retrieves the specific subkey.

5.4.3 XMSS-MT signing

5.4.3.1 XMSS-MT treeSig

The treeSig algorithm generates a WOTS+ signature for a message with a given authentication path.

Algorithm: treeSig(M' , SK , idx_sig , $ADRS$)

Input: n -byte message M' , XMSS private key SK , signature index idx_sig , $ADRS$

Output: WOTS+ signature sig_ots and authentication path $auth$

Steps:

- a) Set $auth = \text{buildAuth}(SK, idx_sig, ADRS)$.
- b) Set $ADRS.type = 0$.
- c) Set $ADRS.OTSAddress = idx_sig$.
- d) $sig_ots = \text{WOTS+}_sign(\text{WOTS+}_generate_privkey(SK.SK_S, idx_sig, ADRS.layerAddress, ADRS.treeAddress), M', SK.SEED, ADRS)$.
- e) Return $sig_ots || auth$.

5.4.3.2 XMSS-MT Signing

This algorithm generates an XMSS-MT signature and updates the XMSS-MT private key. This algorithm requires an authentication path computation algorithm. A simple authentication path computation algorithm is provided in 5.3.5. It should be noted that the XMSS-MT signing algorithm modifies the private key given the index update process. The XMSS-MT signing algorithm uses the treeSig algorithm as an intermediate step.

Algorithm: XMSS_MT_sign(SK_MT , m).

Input: Private key SK_MT , message m .

Output: Updated private key SK_MT and Signature Sig_MT .

Steps:

- a) Set $ADRS = \text{toByte}(0, 32)$.
- b) Set $SEED = SK_MT.SEED$.
- c) Set $SK_PRF = SK_MT.SK_PRF$.
- d) Set $idx_sig = SK_MT.idx$.
- e) Set $SK_MT.idx = idx_sig + 1$.
- f) Set $r = \text{PRF}(SK_PRF, \text{toByte}(idx_sig, 32))$.
- g) Set $M' = H_msg(r || SK_MT.root || \text{toByte}(idx_sig, n), m)$.
- h) Set $Sig_MT = idx_sig$.
- i) Let idx_tree be the $(h - (h / d))$ most significant bits of idx_sig .
- j) Let idx_leaf be the (h / d) least significant bits of idx_sig .
- k) Set $SK = idx_leaf || \text{getXMSS_SK}(SK_MT, idx_tree, 0) || SK_PRF || \text{toByte}(0, n) || SEED$.
- l) Set $ADRS.layerAddress = 0$.
- m) Set $ADRS.treeAddress = idx_tree$.

- n) Set $Sig_tmp = treeSig(M', SK, idx_leaf, ADRS)$.
- o) Set $Sig_MT = Sig_MT || r || Sig_tmp$.
- p) For j from 1 to $d - 1$:
 - 1) Set $root = treeHash(SK, 0, h / d, ADRS)$.
 - 2) Let idx_leaf be the (h / d) least significant bits of idx_tree .
 - 3) Let idx_tree be the $(h - j * (h / d))$ most significant bits of idx_tree .
 - 4) Set $XMSS_SK = getXMSS_SK(SK_MT, idx_tree, j)$.
 - 5) Set $SK = idx_leaf || XMSS_SK || XMSS_SK.SK_PRF || toByte(0, n) || SEED$.
 - 6) Set $ADRS.layerAddress = j$.
 - 7) Set $ADRS.treeAddress = idx_tree$.
 - 8) Set Sig_tmp to be $treeSig(root, SK, idx_leaf, ADRS)$.
 - 9) Set Sig_MT to be $Sig_MT || Sig_tmp$.
- q) Return $SK_MT || Sig_MT$.

It should be noted that signatures produced in step p) can be cached and only computed once.

5.4.4 XMSS-MT Verification

This algorithm verifies if an XMSS-MT signature is authentic.

Algorithm: $XMSS_MT_verify(Sig_MT, PK_MT, m)$.

Input: Signature Sig_MT , public key PK_MT , message m .

Output: *VALID* or *INVALID*.

Steps:

- a) Set $idx_sig = Sig_MT.idx$.
- b) Set $SEED = PK_MT.SEED$.
- c) Set $ADRS = toByte(0, 32)$.
- d) Set $M' = H_msg(Sig_MT.R || PK_MT.Root || (toByte(idx_sig, n)), m)$.
- e) Let idx_leaf be the (h / d) least significant bits of idx_sig .
- f) Let idx_tree be the $(h - h / d)$ most significant bits of idx_sig .
- g) Set $Sig' = getXMSSSignature(Sig_MT, 0)$.
- h) Set $ADRS.layerAddress = 0$.
- i) Set $ADRS.treeAddress = idx_tree$.
- j) Set $Sig'.idx = idx_leaf$.
- k) Set $node = XMSS_rootFromSig(Sig', M', PK_MT, ADRS)$.
- l) For j from 1 to $d - 1$:
 - 1) Set idx_leaf to be the (h / d) least significant bits of idx_tree .

- 2) Set idx_tree to be the $(h - j \cdot h/d)$ most significant bits of idx_tree .
 - 3) Set $Sig' = \text{getXMSSSignature}(Sig_MT, j)$.
 - 4) Set $ADRS.layerAddress = j$.
 - 5) Set $ADRS.treeAddress = idx_tree$.
 - 6) Set $Sig'.idx = idx_leaf$.
 - 7) Set $node = \text{XMSS_rootFromSig}(Sig', node, PK_MT, ADRS)$.
- m) If $node$ is equal to $PK_MT.root$, then return *VALID*.
- n) If $node$ is not equal to $PK_MT.root$, then return *INVALID*.

$\text{getXMSSSignature}(Sig_MT, i)$ denotes the function that returns the i -th XMSS signature from an XMSS-MT signature.

5.5 Suggested parameters

This document provides sets of parameters based on SHA2-256, SHA2-256/192 (SHA2-256 truncated to the most significant 24 bytes), or SHAKE256 with an output size of n bytes. The output digest length is represented as a parameter n which is given in bytes, i.e. $n = 24$ or $n = 32$.

Besides having different choices for the underlying hash function and the output length, they also differ in terms of h (height of the tree), which can be: 10, 16 or 20, for XMSS and 20, 40, 60 for XMSS-MT, respectively, and d (the number of multi-trees in XMSS-MT). All XMSS and XMSS-MT parameters use a single value for the Winternitz parameter, $w = 16$, to be consistent with other XMSS published standards.

The parameters for XMSS and XMSS-MT, including their type code and corresponding private key, public key and signature sizes, are listed in [Table 2](#) and [Table 3](#), respectively.

Table 2 — XMSS sizes (in bytes)

Type Code for SHA2-256	Type Code for SHAKE256	n	h	w	Private key size ($4n + 8$)	Public key size ($2n + 4$)	Signature size ($8+n + (len+h) * n$)
0x00000001	0x00000010	32	10	16	136	68	2 504
0x00000002	0x00000011	32	16	16	136	68	2 696
0x00000003	0x00000012	32	20	16	136	68	2 824
0x0000000D	0x00000013	24	10	16	104	52	1 496
0x0000000E	0x00000014	24	16	16	104	52	1 640
0x0000000F	0x00000015	24	20	16	104	52	1 736

Table 3 — XMSS-MT sizes (in bytes)

Type Code for SHA2-256	Type Code for SHAKE256	n	h	d	w	Private key size $\text{ceil}(h/8) + 3n + 4$	Public key size $2n + 4$	Signature size $\text{ceil}(h/8) + n + (h + d * len) * n$
0x00000001	0x00000029	32	20	2	16	103	68	4 963
0x00000002	0x0000002A	32	20	4	16	103	68	9 251
0x00000003	0x0000002B	32	40	2	16	105	68	5 605
0x00000004	0x0000002C	32	40	4	16	105	68	9 893
0x00000005	0x0000002D	32	40	8	16	105	68	18 469
0x00000006	0x0000002E	32	60	3	16	109	68	8 392
0x00000007	0x0000002F	32	60	6	16	109	68	14 824
0x00000008	0x00000030	32	60	12	16	109	68	27 688
0x00000021	0x00000031	24	20	2	16	79	52	2 955

Table 3 (continued)

Type Code for SHA2-256	Type Code for SHAKE256	n	h	d	w	Private key size $\text{ceil}(h/8) + 3n + 4$	Public key size $2n + 4$	Signature size $\text{ceil}(h/8) + n + (h + d * \text{len}) * n$
0x00000022	0x00000032	24	20	4	16	79	52	5 403
0x00000023	0x00000033	24	40	2	16	81	52	3 437
0x00000024	0x00000034	24	40	4	16	81	52	5 885
0x00000025	0x00000035	24	40	8	16	81	52	10 781
0x00000026	0x00000036	24	60	3	16	85	52	5 145
0x00000027	0x00000037	24	60	6	16	85	52	8 817
0x00000028	0x00000038	24	60	12	16	85	52	16 161

6 LMS and HSS schemes

6.1 Byte ordering convention

The functions $u8str(x)$, $u16str(x)$, and $u32str(x)$ convert an unsigned integer to a sequence of bytes of length 1, 2, and 4, respectively. The reverse operations are defined with the respective functions $strtou8(x)$, $strtou16(x)$, and $strtou32(x)$.

6.2 Converting to base 2^W

Algorithm: $\text{coef}(x, i, W)$

Input: A byte string x , index i and base W in $\{1, 2, 4, 8\}$.

Output: The i th W -bit value of x , when interpreting x as a sequence of W -bit values.

Steps:

- Set $tmp = x[\text{floor}(i * W / 8)]$. Here, $x[j]$ is the j -th byte from x .
- Set $tmp = tmp \gg (8 - (W * (i \bmod (8 / W)) + W))$.
- Return $(2^W - 1) \& tmp$.

6.3 Checksum Calculation

Algorithm: $\text{checksum}(x, W)$

Input: A byte string x of length l and base 2^W .

Output: The checksum for x as a 16-bit unsigned integer.

Steps:

- Set $sum = 0$
- Set $len_1 = \text{ceil}(8 * l / W)$
- Set $len_2 = \text{ceil}(\text{floor}(\text{lb}((2^W - 1) * len_1) + 1) / W)$
- Set $ls = 16 - (len_2 * W)$
- For i from 0 to $(l * 8 / W) - 1$, set $sum = sum + (2^W - 1) - \text{coef}(x, i, W)$.
- Return $(sum \ll ls)$.

6.4 Type code

A type code is an unsigned integer that is associated with a particular format of LM-OTS, LMS, and HSS. All signatures and public keys use a 4-byte typecode which specifies the precise details of the format. The typecode specifies the values for n and W , and the hash function to use for H .

6.5 LM-OTS

6.5.1 General

[6.5](#) defines the LM-OTS signature scheme. LM-OTS is a one-time signature scheme used as a building block for both LMS and HSS. LM-OTS shall not be used outside the context of LMS or HSS. LM-OTS has the following parameters:

- n : Output size of the hash function in bytes. This shall be 24 or 32.
- W : This shall be 1, 2, 4 or 8. It should be noted that in LMS/HSS, this parameter is the log of the same parameter used in XMSS.
- H : The cryptographic hash function used in LM-OTS. This shall be SHA2-256 (Dedicated Hash-Function 4 defined in ISO/IEC 10118-3), SHA256/192 (SHA2-256 truncated to the most significant 24 bytes) or SHAKE256 with an output size of n (see ISO/IEC 10118-3:2018, C.2).

The parameter n determines the security of LM-OTS. The parameter W determines the length of the hash chains in the scheme, which influences the signature size and computation time.

The LM-OTS key generation, signing and verification further take the following parameters into account:

- I : This is a 16-byte identifier which indicates which Merkle tree this LM-OTS is used with.
- q : This is a 32-bit integer that indicates the leaf of the Merkle tree where the LM-OTS public key is used.
- len : The number of n -byte string elements that make up an LM-OTS signature.

The value len is fully determined by n and W , and computed as follows:

- $len_1 = \text{ceil}(8*n/W)$.
- $len_2 = \text{ceil}(\text{floor}(\text{lb}((2^W - 1) * len_1)) + 1) / W$.
- $len = len_1 + len_2$.

A unique parameter set name is associated with each parameter set. For example, LMOTS_SHA256_N32_W4 refers to LM-OTS using SHA2-256 with $n = 32$ and $W = 4$.

6.5.2 Key generation

6.5.2.1 Private Key

Algorithm: LMOTS_generate_privkey($I, q, type$).

Input: An identifier I , the leaf index q , the 4-byte typecode $type$.

Output: LM-OTS private key.

Steps:

- a) Generate len n -byte strings $x[0], \dots, x[len-1]$ from the output generation function of an RBG.
- b) Output private key $k = \text{u32str}(type) || I || \text{u32str}(q) || x[0] || x[1] || \dots || x[len-1]$.

An LM-OTS private key shall be used to sign at most one message.

6.5.2.2 Private Key (from seed)

Alternatively, a private key can be generated from an n -byte seed $SK.S$.

Algorithm: LMOTS_generate_privkey_from_seed($l, q, SK.S, type$).

Input: An identifier l , the leaf index q , the n -byte seed $SK.S$, the 4-byte typecode $type$.

Output: LM-OTS private key.

Steps:

- a) for i from 0 to $len - 1$:
 - 1) $x[i] = H(l \parallel u32str(q) \parallel u16str(i) \parallel u8str(0_{\times ff}) \parallel SK.S)$.
- b) Return private key $k = u32str(type) \parallel l \parallel u32str(q) \parallel x[0] \parallel x[1] \parallel \dots \parallel x[len-1]$.

An LM-OTS private key shall be used to sign at most one message.

6.5.2.3 Public Key

The LM-OTS public keys are generated from the private key in the following way:

Algorithm: LMOTS_generate_pubkey(k).

Input: LM-OTS private key k .

Output: LM-OTS public key.

Steps:

- a) Extract the values $l, q, type$ and $x[]$ from k .
- b) For i from 0 to $len - 1$:
 - 1) Set $tmp = x[i]$.
 - 2) For j from 0 to $2^W - 2$, set $tmp = H(l \parallel u32str(q) \parallel u16str(i) \parallel u8str(j) \parallel tmp)$.
 - 3) Set $y[i] = tmp$.
- c) Set $K = H(l \parallel u32str(q) \parallel u16str(0_{\times 8080}) \parallel y[0] \parallel \dots \parallel y[len-1])$.
- d) Return $u32str(type) \parallel l \parallel u32str(q) \parallel K$.

6.5.3 Signing

Algorithm: LMOTS_sign(m, k).

Input: Message m to be signed, LM-OTS private key k .

Output: Signature s for message m .

Steps:

- a) Extract the values l, q, x and $type$ from k .
- b) Let C be an n -byte string from the output generation function of an RBG.
- c) Set $M' = H(l \parallel u32str(q) \parallel u16str(0_{\times 8181}) \parallel C \parallel m)$.
- d) For i from 0 to $len - 1$:
 - 1) Set $a = coef(M' \parallel checksum(M', W))$.

- 2) Set $tmp = x[i]$.
 - 3) For j from 0 to $a - 1$, set $tmp = H(I \parallel u32str(q) \parallel u16str(i) \parallel u8str(j) \parallel tmp)$.
 - 4) Set $y[i] = tmp$.
- e) Return $u32str(type) \parallel C \parallel y[0] \parallel \dots \parallel y[len-1]$.

6.5.4 Verification

Verifies if a signature is authentic given a signature, a public key and a message. The LM-OTS verification process is divided into two parts. The first is to recompute the LM-OTS public key from the LM-OTS signature. The second is to check if the recomputed LM-OTS public key matches the original one.

When used in the context of LMS or HSS signature verification, only the first part of the LM-OTS verification process is performed, i.e. the LM-OTS public key recovery step. It is never compared with any other LM-OTS public key. This verification is implicitly done at the LMS or HSS signature verification level.

Algorithm: LMOTS_pubkey_from_sig(m, s, pub_key).

Input: Message m , signature s , the LMS public key pub_key .

Output: The recomputed LM-OTS public key Kc .

Steps:

- a) Parse s , to obtain C and $y[0], \dots, y[len - 1]$. Parse pub_key to obtain I and q .
- b) Set $M' = H(I \parallel u32str(q) \parallel u16str(0 \times 8181) \parallel C \parallel m)$.
- c) For i from 0 to $len - 1$:
 - 1) Set $a = \text{coef}(M' \parallel \text{checksum}(M', W))$.
 - 2) Set $tmp = y[i]$.
 - 3) For j from a to $2^W - 2$, set $tmp = H(I \parallel u32str(q) \parallel u16str(i) \parallel u8str(j) \parallel tmp)$.
 - 4) Set $z[i] = tmp$.
- d) Set $Kc = H(I \parallel u32str(q) \parallel u16str(0 \times 8080) \parallel z[0] \parallel z[1] \parallel \dots \parallel z[len-1])$.
- e) Return Kc .

6.5.5 Suggested Parameters

The suggested parameters for LM-OTS can be found in [Table 4](#).

Table 4 — LM-OTS parameter sets

Type Code for SHA2	Type Code for SHAKE	n	W
0x00000001	0x00000009	32	1
0x00000002	0x0000000A	32	2
0x00000003	0x0000000B	32	4
0x00000004	0x0000000C	32	8
0x00000005	0x0000000D	24	1
0x00000006	0x0000000E	24	2
0x00000007	0x0000000F	24	4
0x00000008	0x00000010	24	8

6.6 LMS

6.6.1 General

The LMS scheme can sign a fixed number of messages. It uses the LM-OTS signature scheme defined in 6.5 and builds a full binary Hash tree where the leaves are the public keys of LM-OTS key pairs. Each node of this tree is associated with a node number. The root is defined to be the node with number 1. For a node with the number N , the left child is defined as the node with number $2*N$ and the right child as the node with number $2*N + 1$.

LMS uses the following parameters:

- h : The height of the tree. This shall be in {5, 10, 15, 20, 25}.
- m : The number of bytes associated with each node. This shall be in {24, 32}. This shall not be confused with the message m .
- H : The cryptographic hash function used in LM-OTS and to generate the Merkle tree nodes in LMS. This shall be SHA2-256, SHA2-256/192 (SHA2-256 truncated to the most significant 24 bytes) or SHAKE256 with an output size of m .
- OTS: An LM-OTS signature scheme with the parameter defined in 6.5. The hash function used in this parameter set shall be the same as in LMS.

An LMS tree will therefore have 2^h leaves, which allows it to sign up to 2^h messages. A parameter set is defined with a unique name LMS_SHA256_M32_H10, which corresponds to an LMS tree using SHA2-256 with $m = 32$ and $h = 10$.

The OIDs for these algorithms shall be in accordance with Annex A. Test vectors can be found in Annex C.

6.6.2 Key generation

The LMS private and public keys are composed of:

Private key:

- q , the leaf index (8 bytes).
- $type$, the type code (4 bytes).
- $otstype$, the type code for the OTS (4 bytes).
- I , the identifier (16 bytes).
- If the method described in 6.5.2.2 is used, a seed SK_S (n bytes)
- If the method described in 6.5.2.1 is used, 2^h LM-OTS private keys ($2^h * len * n$ bytes).

An LMS private key consists of 2^h LM-OTS private keys (or, alternatively, a seed SK_S which is used to derive these LM-OTS private keys); an index q , which indicates which private LM-OTS key should be used next; and the identifier I . The value q shall be initialized to 0. Each LM-OTS key shall be generated with a different value q . LM-OTS are indexed sequentially from 0 to $2^h - 1$. The LM-OTS key pairs used here are referred to as $(LM_OTS_PUB_KEY[i], LM_OTS_PRIVATE_KEY[i])$, for i in $0, \dots, 2^h - 1$. Set I to be 16 bytes output from an RBG.

Public key:

- $type$, the type code (4 bytes).
- $otstype$, the type code for the OTS (4 bytes).
- I , the identifier (16 bytes).
- $T[1]$, the root element of the tree (m bytes).

An LMS public key is defined as the root of the binary Hash tree. In order to compute the root, the following process shall be used. The string for the N -th node is denoted here as $T[N]$, and the nodes are indexed from 1 to $2^{(h+1)} - 1$:

a) If a node is a leaf node (this means $N \geq 2^h$), then the value corresponding to the node is:

$H(I \parallel \text{u32str}(N) \parallel \text{u16str}(0 \times 8282) \parallel \text{get } K \text{ component from within concatenated string } LM_OTS_PUB_KEY[N - 2^h])$

b) Otherwise the node is computed as:

$H(I \parallel \text{u32str}(N) \parallel \text{u16str}(0 \times 8383) \parallel T[2*N] \parallel T[2*N + 1])$

c) Output the LMS public key as:

$\text{u32str}(type) \parallel \text{u32str}(otstype) \parallel I \parallel T[1]$

6.6.3 Signing

An LMS signature consists of three parts:

- The number q corresponding to the leaf index used in this signature. This is a 4-byte value.
- An LM-OTS signature and the typecode indicating which LMS algorithm is used.
- An array of h m -byte values, which are the authentication path.

The authentication path is the minimal number of nodes required, such that someone verifying the signature can recompute the root of the binary Hash tree from the authentication path and the LM-OTS signature.

Algorithm: $LMS_sign(m, k)$.

Input: Message m to be signed, LMS private key k .

Output: Signature s for message m .

Steps:

- a) Let q_sig be the current index q .
- b) Update index q to the next unused index.
- c) Compute an LM-OTS signature of the message m , using the LM-OTS key pair corresponding to the index q_sig from the LMS private key k .
- d) Compute the authentication path.
- e) Set $s = \text{u32str}(q_sig) \parallel lmots_signature \parallel \text{u32str}(type) \parallel path[0] \parallel path[1] \parallel path[2] \parallel \dots \parallel path[h-1]$

Any implementation of LMS_sign shall ensure that the index q is updated before a signature is released.

6.6.4 Verification

Algorithm: $LMS_verify(m, public_key, s)$.

Input: Signature s , message m to be verified, LMS public key $public_key$.

Output: *VALID* if the signature is correct, otherwise *INVALID*.

Steps:

- a) Let lms_type be the type in $public_key$.
- b) Let sig_type be the type in s .
- c) If lms_type does not equal sig_type , return *INVALID*.

- d) Extract the LM-OTS signature s_{ots} using the index q from s , and compute the value Kc using $LMOTS_pubkey_from_sig(m, s_{ots}, public_key)$.
- e) Compute the root node candidate Tc for the LMS tree in the following way:
- 1) Set $node_num = 2^h + q$.
 - 2) Set $tmp = H(I || u32str(node_num) || u16str(0 \times 8282) || Kc)$.
 - 3) Set $i = 0$.
 - 4) while $node_num > 1$ do:
 - i) $parent_node_num = \text{floor}(node_num / 2)$
 - ii) If $node_num$ is odd, set
 $tmp = H(I || u32str(parent_node_num) || u16str(0 \times 8383) || path[i] || tmp)$.
 - iii) If $node_num$ is even, set
 $tmp = H(I || u32str(parent_node_num) || u16str(0 \times 8383) || tmp || path[i])$.
 - iv) Set $node_num = parent_node_num$.
 - v) Set $i = i + 1$.
 - 5) Set $Tc = tmp$.
- f) If Tc is equal to the value $T[1]$ in the public key, then the output is *VALID*. Otherwise, the signature shall be rejected and the output is *INVALID*.

6.6.5 Suggested Parameters

The suggested parameters for LMS can be found in [Table 5](#).

Table 5— LMS sizes (in bytes)

Type Code for SHA2	Type Code for SHAKE	n	h
0x00000005	0x0000000F	32	5
0x00000006	0x00000010	32	10
0x00000007	0x00000011	32	15
0x00000008	0x00000012	32	20
0x00000009	0x00000013	32	25
0x0000000A	0x00000014	24	5
0x0000000B	0x00000015	24	10
0x0000000C	0x00000016	24	15
0x0000000D	0x00000017	24	20
0x0000000E	0x00000018	24	25

6.7 HSS

6.7.1 General

Using a very large number of nodes in a tree is costly, owing to the effort for generating a key pair scales with the size of the tree. If a large number of signatures are required to be supported, the hierarchical signature scheme (HSS) can be used.

HSS uses the following parameters:

- L : The number of layers of LMS trees used. L shall be between 1 and 8, inclusive.

All layers shall use the same hash function. For each layer, the same LMS and LM-OTS parameter set shall be used. Different layers may use a different set of LMS and LM-OTS parameters.

The OIDs for these algorithms shall be in accordance with [Annex A](#). Test vectors can be found in [Annex C](#).

6.7.2 Key generation

The HSS private and public keys are composed of:

Private key:

- q , the leaf index (8 bytes).
- $u32str(L)$, the number of layers (4 bytes).
- $type$, the type code (4 bytes) .
- $otstype$, the type code for the OTS (4 bytes).
- I , the identifier (16 bytes).
- If the method described in 6.5.1.2 is used, a seed SK_S (n bytes)
- If the method described in 6.5.1.1 is used, 2^h LM-OTS private keys ($2^h * len * n$ bytes).

Public key:

- $u32str(L)$, the number of layers (4 bytes).
- $type$, the type code (4 bytes) .
- $otstype$, the type code for the OTS (4 bytes).
- I , the identifier (16 bytes).
- $T[1]$, the root element of the tree (m bytes).

If different LMS and LM-OTS parameters are used across the layers, then the private and public key shall contain the $type$ and $otstype$ for each individual layer.

An HSS key pair is generated in the following way:

- a) Generate an LMS key pair. The corresponding private key is $prv[0]$ and public key $pub[0]$.
- b) For each i from 1 to $L - 1$.
 - 1) Generate an LMS key pair. The corresponding private key is assigned to $prv[i]$ and the public key to $pub[i]$.
 - 2) Sign $pub[i]$ using $prv[i - 1]$ with LMS. This computes the signature $sig[i - 1] = LMS_sign(pub[i], prv[i - 1])$.

The HSS private key consists of the values $prv[0], \dots, prv[L-1], pub[0], \dots, pub[L-1]$, and $sig[0], \dots, sig[L-2]$. It is not necessary to keep secret the values pub and sig . The values $prv[1], \dots, prv[L-1]$ and $pub[1], \dots, pub[L-1]$ are updated during signature generation.

The public key of HSS is the root node of the LMS tree at layer 0 and the number of layers: $u32str(L) || type || otstype || I || pub[0]$.

6.7.3 Signing

To sign a message m with HSS, the following steps are completed:

- a) Check if the LMS key $prv[L-1]$ can still sign messages:
 - 1) If it can still sign messages, then sign m with the LMS key and set $sig[L-1]$ to the value of the signature.
 - 2) If the number of signatures for the LMS key $prv[L-1]$ is exhausted, find the smallest value d such that $prv[d], prv[d+1], \dots, prv[L-1]$ are exhausted.
 - i) If d is equal to 0, then the HSS key pair is exhausted and no further signature shall be generated with this HSS key pair.
 - ii) If d is not equal to 0, then new LMS key pairs are generated for each layer i from d to $L-1$ as follows:
 - (A) Generate a new LMS key pair and assign it to $prv[i]$ and $pub[i]$.
 - (B) Sign the value $pub[i]$ with $prv[i - 1]$, and set $sig[i - 1]$ to the resulting value.
 - iii) Sign m with $prv[L - 1]$ and set $sig[L-1]$ to the resulting value.
- b) The HSS signature is then defined as:

$$u32str(L - 1) \parallel sig[0] \parallel pub[1] \parallel \dots \parallel pub[L-1] \parallel sig[L-1]$$

The algorithm above assumes that the LMS signing algorithm updates the state prv , thus preventing key reuse.

6.7.4 Verification

To verify a signature S , for a message M , with the public key $pubkey$, perform the following steps:

- a) Set $Nspk$ = first four bytes of S .
- b) If $Nspk+1$ is not equal to the number of levels L in pub :
 - 1) return *INVALID*.
- c) For ($i = 0; i < Nspk; i = i + 1$):
 - 1) Set $siglist[i]$ = next LMS signature parsed from S .
 - 2) Set $publist[i]$ = next LMS public key parsed from S .
- d) Set $siglist[Nspk]$ = next LMS signature parsed from S .
- e) Set $key = pub$.
- f) For ($i = 0; i < Nspk; i = i + 1$)
 - 1) Set $sig = siglist[i]$.
 - 2) Set $msg = publist[i]$.
 - 3) If ($lms_verify(msg, key, sig)$ is not *VALID*):
 - i) return *INVALID*.
 - 4) Set $key = msg$.
- g) return $lms_verify(M, key, siglist[Nspk])$.

6.7.5 Suggested Parameters

Each LMS tree in an HSS instance shall use a parameter set from [Table 5](#). Additionally, all LMS instances shall use the same hash function. A specific level in an HSS instance shall use the same LMS and LM-OTS parameter sets. Different LMS and LM-OTS may be used on different levels, as long as the same hash function is used.

7 State management

One of the main challenges for the deployment of stateful hash-based signatures schemes refers to the process of state management, i.e. the ability to ensure that a signature state is never re-used. This is necessary for security purposes. The stateful HBS schemes defined in this document are based on one-time signature (OTS) building blocks which lose their security guarantees if the same OTS private key is used more than once (see Reference [7] for a comprehensive assessment of the security impact of reusing the same OTS private key). The problem of state management is well-known in the literature (see Reference [8]), and therefore this clause presents requirements for practitioners to implement robust state management mechanisms.

- a) The state used by the stateful HBS schemes defined in this document is a piece of information that shall be stored, maintained and otherwise updated for the whole lifespan of the private key. Therefore, the state shall be stored in a secure non-volatile memory region inside the signing module. A hardware security module (HSM) is recommended to be used for this purpose to prevent users' access to the state and make the process of updating the state transparent to the signers.
- b) Once a signature request is received, the signer shall first update the state and only then start the signing procedure. If this process was done in reverse order, there is a risk that the signature is produced but the state remains in its previous value (for example, due to a fault in the equipment occurring right after the signature is produced). In other words, the ultimate goal is ensuring that these two processes are performed in an atomic fashion.

Other mechanisms to prevent state re-use may be used.

Annex A (normative)

Object identifiers and ASN.1 module

This annex lists the object identifiers assigned to the digital signature mechanisms specified in this document, namely: XMSS, XMSS-MT, LMS, and HSS. It should be noted that the additional information required for interoperability such as the selected parameter set or the selected hash function are given in the *type* field, which is part of the public key and signature data structures as specified in [5.5](#), [6.5.5](#), and [6.6.5](#).

```

DigitalSignatureWithAppendixStatefulHash
  {iso(1) standard(0) digital-signature-with-appendix (14888) part4(4)
   asn1-module(1) stateful-hash-based-mechanisms(0) version1(1)}

DEFINITIONS EXPLICIT TAGS ::= BEGIN

id-isoiecl4888-4 OBJECT IDENTIFIER ::=
  {iso(1) standard(0) digital-signature-with-appendix(14888) part4(4)}
id-14888-4-algorithms OBJECT IDENTIFIER ::= {id-isoiecl4888-4 algorithm(0)}

id-dswa-sfh-xmss OBJECT IDENTIFIER ::= { id-14888-4-algorithms 1 }
id-dswa-sfh-xmssmt OBJECT IDENTIFIER ::= { id-14888-4-algorithms 2 }
id-dswa-sfh-lms OBJECT IDENTIFIER ::= { id-14888-4-algorithms 3 }
id-dswa-sfh-hss OBJECT IDENTIFIER ::= { id-14888-4-algorithms 4 }

alg-dswa-sfh-xmss ALGORITHM ::= {
  PARMS      Param-dswa-sfh-xmss
  IDENTIFIED BY { id-dswa-sfh-xmss } }

Param-dswa-sfh-xmss ::= OCTET STRING (SIZE (4)) -- xmss-id

alg-dswa-sfh-xmssmt ALGORITHM ::= {
  PARMS      Param-dswa-sfh-xmssmt
  IDENTIFIED BY { id-dswa-sfh-xmssmt } }

Param-dswa-sfh-xmssmt ::= OCTET STRING (SIZE (4)) -- xmssmt-id

alg-dswa-sfh-lms ALGORITHM ::= {
  PARMS      Param-dswa-sfh-lms
  IDENTIFIED BY { id-dswa-sfh-lms } }

Param-dswa-sfh-lms ::= SEQUENCE {
  lms-id      OCTET STRING (SIZE (4)),
  lms-ots-id  OCTET STRING (SIZE (4)) }

alg-dswa-sfh-hss ALGORITHM ::= {
  PARMS      Param-dswa-sfh-hss
  IDENTIFIED BY { id-dswa-sfh-hss } }

-- The SEQUENCE encodes LMS tree parameters in order from layer 0 to layer L-1
Param-dswa-sfh-hss ::= SEQUENCE SIZE (1..8) OF Param-dswa-sfh-lms

-- Copied from Rec. ITU-T X.509 | ISO/IEC 9594-8:

ALGORITHM ::= CLASS {
  &Type      OPTIONAL,
  &DynParms  OPTIONAL,
  &id        OBJECT IDENTIFIER UNIQUE }
WITH SYNTAX {
  [PARMS      &Type]
  [DYN-PARMS  &DynParms ]
  IDENTIFIED BY &id }

AlgorithmIdentifier{ALGORITHM:SupportedAlgorithms} ::= SEQUENCE {

```

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```
algorithm      ALGORITHM.&id({SupportedAlgorithms}),  
parameters    ALGORITHM.&Type({SupportedAlgorithms}{@algorithm}) OPTIONAL }
```

```
SupportedAlgorithms ALGORITHM ::= {  
  alg-dswa-sfh-xmss |  
  alg-dswa-sfh-xmssmt |  
  alg-dswa-sfh-lms |  
  alg-dswa-sfh-hss, ... }
```

```
END -- DigitalSignatureWithAppendixHash
```

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Annex B
(informative)

Relation to other standards

The parameters provided in this document are consistent with the parameters given in NIST SP 800-208^[1] and include a subset of the parameters given in IRTF RFC-8391.^[2] This document does not include the RFC-8391 parameters based on $n = 64$ and those based on SHAKE128.

This document is currently limited to the hash functions SHA2-256 and SHAKE256, which have been used to instantiate XMSS in the RFC-8391^[2] and LMS in Reference [3]. At the time of publication of this document, these hash functions are the only instantiations which have been published for a sufficient amount of time to be considered mature.

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Annex C
(informative)

Numerical examples

C.1 General

In this annex, the public key, message and signature are expressed in hexadecimal notation. The private key is given as a sequence in byte following the order defined in 5.3.3.1, 6.6.2 and 6.7.2. The private keys here are examples and shall never be used in practice.

C.2 XMSS

C.2.1 XMSS SHA2-256

Parameters: $n=32, h=10, w=16$

Private key:

00000200 00010203 04050607 08090A0B 0C0D0E0F 10111213 14151617 18191A1B 1C1D1E1F 20212223
 24252627 28292A2B 2C2D2E2F 30313233 34353637 38393A3B 3C3D3E3F 9D898033 E37AF48E 6A116F8B
 15651CC2 67734670 07AD1937 5D38C23C 690C3483 40414243 44454647 48494A4B 4C4D4E4F 50515253
 54555657 58595A5B 5C5D5E5F

Public key:

00000001 9D898033 E37AF48E 6A116F8B 15651CC2 67734670 07AD1937 5D38C23C 690C3483 40414243
 44454647 48494A4B 4C4D4E4F 50515253 54555657 58595A5B 5C5D5E5F

Message: 25

Signature:

00000200 8FF0300B E485DEA7 E5AE2C56 080302FE BC91B413 18C504F8 95BAAB0B 068968F2 22E5DD2E
 120538CB 72D11267 ECF55F62 8970B641 643310F0 39BE9757 C5FA9D80 F71884E3 2447BA71 B4FF1C50
 AD4211C5 D1075BEC A1A9F757 30F91222 E4C89C6D 1E4E06D0 A222053A 607B34A5 420FD7FF 8A1336A4
 DA238C23 42D210EE EE69C469 751A6E7B D52DFB25 D0C63273 35A873FB 4C4E98D8 185FDD47 9D7A6B1D
 40E1E39A 47FF0DB1 4937F33B 3103915A 9D432FA6 4142BF30 E6F53540 19C3B3A3 55883940 6C67B113
 988587F9 DDFAC790 22730E5F AA222914 4E0FE186 14A7AE52 DB820266 A0A1F8BE 7D0E80DF BC9B6DAE
 74319DE3 7C5255CA 3A70F0DF A85BA1B3 94ACE609 9447C3D9 D14A9497 CF483D4C 4A87E20B D0279AC0
 6C8F58AE E923D4C7 7081CCCC EAE74869 1F1BC9E8 8E3DEF45 A0FA7807 6A066DC5 B3F3E790 34D42891
 F29DF451 C245036F B7AF6D76 0E7BD436 537BD6A7 D0B8903D 1C56399B 2A95CDBD 3C0BB251 12ED77A1
 2BCAB58D ECDC0817 6A105910 CE145A9C 57227AB6 D595E50C 063422A3 F8503847 AC6C0101 7F535A4B
 36F2FB6A FC04948D 626EC2F7 A92555B4 61359521 2751DFA4 40E11664 DD9D9DFC 44AFB661 D1A953A7
 C3E22570 A629D499 42892BF2 B5F72C00 A9A1B166 56E6F7EF 9D5BD7D0 865EEC8A 745164FD D7542C8B
 E4E7B71D 2CD79B79 94BCA264 B4F0F348 46A4E6E7 501B2649 EFC0C466 F590525A 45270876 E2E94000
 D6918E7A BE489DD5 0CB299A9 7CF861B8 89887CF2 023DA55E 521927C4 7D40DE41 3593BD96 44435085
 BE3FFD5E EA1DCE50 D996D3DA 8971B2EB DEA1ABCC 02352922 EB1C75A2 0C79C8D2 914B12FC 3300266E
 B78E2378 C4887E0F D9ED8905 C46F6350 C2B3122E 19962EA2 3113DE6B CFE0D5B9 BBFE68C4 BD25A777
 F249D2BE AFBAA7B9 81C5A1B9 84007208 D53A65A4 F709E281 FCDC5795 B94E3967 A30437CE D628744C
 7B2EA492 FA729683 8A791E82 68363A11 9E3BB780 C7C7B130 070B2B37 5025EF74 85FCD628 4119D235
 DABD8EC1 A7768260 17E2D6ED 4CECF209 0A44F394 CEA92902 AE21A83A 2F2775FA 4695671A 2DF09A07
 80ECB4DF 7F41EDC5 04817E89 CC632FEC 6EA1716A 14B44BCF 4704BBBF F6A014A0 01660EAA 5DF779A7
 A033B3FA 91748C55 30A176C7 898671E5 7F324254 FDA2A0B8 10DE218C 4AA13E08 D9ABE307 0B4A8151
 A70F0208 8B591012 6701F0A8 B2475C1D 7711AB56 A79AFD9B DC09622C 95D144D9 DE7A02D5 06304764
 FF9936F7 4D4D0FF6 E4E6C6ED E0DB7516 652E95CC 92368D45 360EBDB1 2199EAFB 216E1B7B 09C6D331
 6E8552E1 69EAE48E FD5C33B1 17879DCF 7DBD3795 327CEAB2 8D8A7C05 BD12654B 0ABC3AA0 CB7390F2
 BB5852D6 D4D13F61 B94CD06E 937B51F1 83844A4A 78D0B79A 9CCB5C87 AA022E13 154370C5 9DDB1E38
 B3FE2FEF 96AE94E8 8B2E3C64 02E6F3BD 87B77101 48A658E9 6DA1FC38 BBC0E2A1 CD192E16 B44D97EA
 4AF81435 03035F37 71345169 E2655326 0DF269F5 11FC1CCF C26B5944 BA2B1052 16BED0AC ED790D1D
 1781BECE F3A39A7C F46A8D13 99E44170 B4D94888 4F6BF701 BB2FE7FC 9D357944 DFCEC17E 49817F3F

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ED983D2C	2D05AC4E	08F41995	95AF5C93	131A59FC	E8E4A283	434C58B5	33EAED10	963C8D2E	4970E83F
1DCE8C07	392F11F7	770E8BCC	C7DA3E71	035AA44F	A7F5F3A2	ACC0D772	78C62120	FCE201B1	C7174340
C83F9E4F	1FA1A24B	7798399F	D665E347	A39E994E	E84E11D7	05CA2017	2C368A12	E1078AAE	F2A7A013
BEDDEBD4	77AF5391	0187CDA2	9F1E0BC1	B435C5BA	C9B6D36E	E627395F	D515FEB8	E7467A4A	B6A8D9D9
32605B7B	73FADF32	90554D5C	2B0C8F11	D9787D4E	1FE9038D	B6A08481	330C9C91	26E7E79B	48EBD471
4615664D	DFD9BD0E	5DD3FBB5	61506679	D3A636C0	AB4A66B4	107F0EF6	978173CE	07D1A0B9	626BA0EC
EE498E3D	7F773F35	9CD7959D	B7578946	D6236177	6CA7E014	673DAB60	791E3F8B	BD553166	1D16D6A9
D6DE7E9F	03931761	55179A27	0BF5EAB7	5B7D6931	16AC288B	13BC0ED9	A0959A84	31AAC33B	169C64A0
3EB2894E	209EC584	5FA1D0FA	C0030483	298319DE	BB6F3C77	5476B627	8008D9EF	ED184446	09111677
FED5BEE0	23842414	DC049437	D5896A14	48F93FF5	30E2C73C	4EA085C2	33268D5D	C4498A30	1FB554C8
2151D393	A5D7935A	6F2996DB	CFDBAA8F	BB34D4B9	83BCBD04	64A2B455	C85623BB	E5BAEC5F	1F5471F3
1BA300C3	135640D9	969E028F	56F62297	FD537D07	4BE35D52	45546BB4	ABDAB540	85C364E1	19A2020A
C2B1EEBD	09CDDDD3A	02257E5C	35A79C9C	988D7D6F	47C99E11	3845F0BE	AE75E0D8	76E91D0D	6B5F6164
5CD52A6F	0F099797	50E3DAE7	11D7FD29	B525804E	9471BB25	8C748297	37001D91	4A5D260F	4BF2401D
DA0C10D5	A5D39E9D	C558A855	728744CD	7BA02135	F46F7598	3D9FFB5C	3D74A44B	9278086F	0C1C1957
175225DC	EBD02C68	2CCA76D1	31584E21	6C2C9224	C9AC81B5	785ECD7F	E17B3BF5	179819F7	F9ED0E6E
976A88FC	51DEF3A3	A33E8EEA	FB9309D9	39D03A39	01A4F5C4	7A0CCA5A	C0EF9937	5C002FB4	538EB451
ECA08C7D	7C537F1B	EF90679E	25D2D701	5B38EE1E	FA663C98	34ED6BDF	2D90849A	3571C0A2	5B36079F
FC389C2B	87797E98	26EAAF28	6E3B4F9F	D9C8AB69	D6FF1B3E	5710B2ED	394B3296	253F78EB	9C3D49F3
1394A8FC	03B41608	CF1CAECA	6E3C5FEF	AB82FD9B	BA0148D7	FAD8DBCD	D478326D	28952B6E	781DDCF6
690ACD70	D5EFC75E	694D6F4A	0496FCB7	76DCB752	14916D1F	B6617F23	491C31C8	A189DC09	0054B0F4
6E9474CC5	EC38B4E1	F9F1D8B2	33075BF0	4CE63776	1E5595E7	A1D7433D	A32E4BCD	E54C3B9F	569B40C1
598705CA	AD5AEF78	AF0BFA00	DFC83824	84FA1AE8	4DBC8F65	2724724D	F4A085B0	43704563	54F3EE86
384D39F2	303F336F	06C95182	5BC56A75	C1279DC8	50F099E1	995ED02A	C172E439	70150987	F8C7F4C6
BDD18FD2	EAB27693	3388CD7F	BA187CCE	AFEE6E52	9CD3961B	5BFEBCC8	7CE11A70	8430C274	CED608D1
790B7D51	BD661E42	1CBA67FC	20C4AF6C	EBF19A3A	C98DCF46	741FE073	05850FAA	75103FB1	C8635007
58BC376D	B06F292A	6E556C9A	C2A1C613	47E7D883	5F132F05	9C3ABC25	868ED9B7	5D80B95E	EF2F3156
67D7D6E2	6045CCF4	87780552	A24B35C5	62505F07	43F6F089	F880E35C	CA8B7E9C	B849670B	1CF06AA5
759C573A	0AEAAB6C	A893460A	7EA15566	94C69514	24FA6B42	C516369C	C9658B81	B325D8D4	86977A69
919F6741	6DD362EF	EE904D96	049E70FA	95A0544A	5ED85A4E	57429CE0	884F7634	50D9EE23	7769DE8C
96B71AD7	9EA5CA55	9B196DBD	B9F96B69	41D0D8A6	F5F1A884	FC6A8028	15DAE957	E40BCE0D	4C8BA500
41DA0B5D	510D3D2F	662DB2F6	353B3A1C	F07B243C	D34346BD	AAFFE5B7	ED4B64F8	CA7BA289	5F339632
92AF7376	538D2831	998CBE8F	076D2231	CC3A5DAD	0DA36CE4	9EEC00E4	0CC3A340	A40FC275	AB1BEA0F
4E976E08	A40D36C8	A6BD049B	F265F1B3	DF85686B	53C623E6	40E3175B	CB84959B	6D1E4695	5E18BC5C
F27D5FE1	3F72589A	395E1EE0	1EB9983D	5CE3E04B					

Parameters: $n=24, h=10, w=16$

Private key:

00000200	00010203	04050607	08090A0B	0C0D0E0F	10111213	14151617	18191A1B	1C1D1E1F	20212223
24252627	28292A2B	2C2D2E2F	B8E84793	033B07D3	E37A24CD	FF2B9636	D47E85B3	5E074EC1	30313233
34353637	38393A3B	3C3D3E3F	40414243	44454647					

Public key:

0000000D	B8E84793	033B07D3	E37A24CD	FF2B9636	D47E85B3	5E074EC1	30313233	34353637	38393A3B
3C3D3E3F	40414243	44454647							

Message: 25

Signature:

00000200	6F827191	2413DCDD	A00FAD02	E64DE5B1	FAD32103	9E6E2136	346E1913	F598FCFE	81246695
48E8228D	43FA606A	18369FFE	C41D48A9	6A9AB2D7	5B826BC0	BE195FA9	7A5DDAE0	77940936	B3BA9764
F603994A	F1F8E273	3D9427B9	D8542C83	2044A640	4EC1F178	50C23180	E3F7CA66	0468F81A	F41A3261
08AFD4A3	77146640	BCC24914	C1A4A7F0	64468F99	C8205CB4	8B5ABED7	76360B13	2A007BB5	A500DA34
1E51D810	A745EF9C	6DA13502	0A404D4A	22D35836	DD9F08BB	2D5DAEEC	B3D7915E	8D962C16	4ACFBFE3
A9DE062B	D4C6CA2B	51B8F4E5	F80A9F75	F1FD0497	4777100D	2DD12571	67B8F648	318EEFB3	55513FB8
3CF3E478	7F256A01	269DFD63	EF55AF35	81721E6B	DOC835B	C7D26A93	8D3310E3	BED9D927	7283D73F
655D56F2	17B50CE8	287BB535	01E94530	350B6E84	29430461	F3685E7C	4690FFD8	DA0628D2	A94915BD
C1F7957B	CEA44A08	908ADEF6	BA340A96	CAE084CD	EA82A038	A2B1ADB8	FDB77273	63603D0A	5093ADA7
B8AF48DB	3274EB8E	00BFA8A7	DEDB916B	E074F6D3	61CB1ABB	BAD1B708	A8509F62	FAB11E0E	6C6335F7
33F4B69F	EF529D73	8AA1EF38	B834C653	2372EB0A	96935BD7	43A00126	5B72FC18	34430D7D	4AC2706C
07CF7AAF	2A0E3525	8AF4408FF	EBE74336	57DB8129	CC627D13	A86E8318	C2B2E067	F8148326	6396A407
81CC0EE3	7ECD4168	9CE41F8E	C641A364	1BC2FCF5	C1D20B9F	B8F794C9	4079FCD9	A3B274E1	7C220396
1193C5C1	D81B60DB	018AD68D	7CC25003	D5D21DD5	708F51CF	7965A73A	148C1D8D	6842944E	10B2DB49
F5A50B09	FDB096A3	721D11E1	96AC2139	63969FE1	C7FEA31B	DBBD26D9	58E0BC25	A301E172	1D44342E
AA0378CD	CDFD6B2B	336A06C2	5A3B28D6	C12E33A3	B87E9564	02BEC553	F47BF0B7	5E096341	4CDEC38F
90015D36	D231B856	9EDA5D8A	F00BB609	4908F208	8B75C43B	36851C1D	FC811F04	A3C8EBE9	4C17E568
5EB01C27	5ADF9B46	29127D5A	41D74C69	BD8D8F65	07DB30B2	C79763B9	4500355D	246EA9A2	512E3985

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4A8ED1FB	A13B72B3	79678412	3C729AF5	404927CD	4F1799F1	B58970B2	3E07F00E	DBFFE5CE	E58D3660
0A0801D1	B3F468E4	E83D84A0	3FD87AB3	E18C1266	CEC592B1	4804BE65	F4AB9906	6F12E686	7518B349
B4416634	87DE6746	80383064	C52A5A87	48739780	6346AEED	F766CFB7	853F1AF8	BC84177A	37C78495
224539C7	2F988B1C	CC64E2FB	C7863F5D	3CCC551C	922EEFFB	467DCF17	511D93CF	14A5C05B	814C1FA2
56FB899C	3D327B9F	F6419BCF	F3B646F4	8BE2A3CE	37D7A583	59FBFD26	1E921155	1FC5EEA6	F363A479
A4688236	25257C81	32B9FC77	8F030F8E	B69A0DEF	C81EA4EC	D9F90BC3	128358D7	903A81DD	27102FDD
571E7ADB	58423A43	9EA24E8D	00E68493	7D0A40DE	9364EED2	69CF4C10	A8DEEC15	A4266F4C	100E09A4
998AA122	48B57543	71409967	E0927A69	D53C55C4	E76884EA	AB2DC64B	F67FA210	AF0C3990	59F4CFFB
F53D44FF	9856355E	1862C5E0	4BDE172F	DE3222EC	BEFDC033	CDD7B93F	3E82C6C8	B03FCBB7	1C03D57E
3017A022	851EA6D0	EAE07490	AB11FBE7	88565A08	9D8D24EE	364F8360	B23C747F	F39E4279	0B2F3E05
96B323A3	FBDE832A	90587FC7	B9C2D469	BF4656BB	3FFF2CF3	154A126A	F2062703	EB8D8F77	D21FC367
710781AE	1E6937C1	51CE2CD5	D14B311B	752A5510	606C7FC9	23C4633D	11DD8FAB	629680F3	58320986
AED6A2F5	FDB51841	F287E636	66A79640	2797FC71	4AE9B2E9	E87993FB	89B84AE7	696F338A	18C6F522
C57C085D	599CFD48	DCBB0B3B	43CA75AA	6C44E58E	33FB5B69	7105DF28	439EFEAE	CB929935	0F10B1DA
63B82622	E4A2095A	C2F9846B	CFB0C8F5	5F4412F1	6E978284	1A881E56	B8AEA36C	8AD667A2	CDC9FFE9
ED05A306	048AC548	1215F6EE	B4B63BA9	53318752	8DB51153	83B66FB7	ACC595F7	ED7A042F	F07EA187
BF093EE6	E8C2EB2F	E0A8868D	F1AB6901	2C7E44BE	6E09CED1	82B5F3B9	B39D6EFA	567FC23A	C8E301BD
52D6740D	637CCAED	4C9BDF44	29B9DC55	6316FA6D	04B18728	C8BAB148	A6035E4A	158B7A66	93DF31E8
DE2AD560	F2ADD6E0	5D8A99DB	2CD5FE1D	90DB2BAD	C9108174	98256609	1F50471D	69D00B71	006CF153
CD378734	7C54E49F	6E5EEF46							

C.2.2 XMSS SHAKE

Parameters: $n=32, h=10, w=16$

Private key:

00000200	00010203	04050607	08090A0B	0C0D0E0F	10111213	14151617	18191A1B	1C1D1E1F	20212223
24252627	28292A2B	2C2D2E2F	30313233	34353637	38393A3B	3C3D3E3F	40414243	44454647	48494A4B
4C4D4E4F	50515253	54555657	58595A5B	5C5D5E5F					

Public key:

00000010	BA62BDC3	9AF136A6	3E66F19D	3CFDA23	2CF5CF48	5AEC1E22	C35D739B	DC511425	40414243
44454647	48494A4B	4C4D4E4F	50515253	54555657	58595A5B	5C5D5E5F			

Message: 25

Signature:

00000200	F88607BA	B61D5412	28CDC83C	1EC48749	3A2D6D05	31EC6E8C	EFC56373	9E2D75F5	1A28FA58
3861267B	9FD945FA	5BD2CEF3	E8D47AF2	6170ADE9	AA77754C	7E900968	9C5C3FEF	FF494DB8	94E54491
383EEACB	FE83FD1B	18CCA27A	5ABE0AE8	D121757B	8BEF01D4	844AFC6A	B5425B48	30AC854D	2D580B1F
EA71B99C	74B6C9CD	17418AA2	C2D55D68	FBFE3445	F26343C2	71EFD032	ECC0BAB8	3226EDA9	COB618CB
DCEC1E8B	AA6FAAD7	008D6D33	7EF99D17	C5705129	1EAD3189	B029702E	E22D86E9	2FF420CF	B84099D1
DBDF0322	48376134	1596C98D	84087701	C227149E	834DE9C6	D7DBA924	F0C4FE64	9BD76B7B	3F3CEED3
09BE524B	71612157	349E3B18	78EF442C	07037690	4C0459C9	7CB812DB	C7350E01	4463FF0F	4C8EFFF4
15B2B9FD	DE09CBD6	5334F390	25B8FB41	468B2ED0	C8D660A1	5034AF80	12D332C1	56094403	367466F7
DD7184FA	050E2D0F	D835A141	E9685742	85CF5CC1	BCB96401	D67B29F9	3774910A	7087C91C	FC4FCAB2
4A9504DC	8C9A8D11	362907F9	913CD523	DADD6B02	DFFB71F1	1599AAF8	0E3668A6	9C0CC9AB	BBA85897
3814D76D	328ECF15	4BFA959B	071B53D8	D852ACC7	1C296373	21F419CF	7BEE9336	3927AA75	01BB83BF
57BBA9FD	8D4F59E3	EA47ED45	32CB3279	088D07AA	DA9DC433	5E420ABA	6F7D9E32	FED1BE7B	FDC51A5D
420D79DC	32969336	F224A6E1	91E52E5D	C063ECF0	BE5D3B69	42E2CDAE	882E4C06	0A9BD16B	07301C54
7755EBED	FD73A231	D437C6A9	07405530	4C1B4CAF	39D8C8EE	557F976C	AAFF8000	4600D7BD	8CFF86D1
C8F314F2	EB03BF69	97694C05	F7A61BC3	E2188436	7A7C045A	2E78B5E7	BCBC4C2B	8C3A2203	5CD1D258
B43A757D	B619B9C3	7A6B9310	CBDBBD8F	6933500B	17221F62	A9ECBF0B	477EBCFB	5645713E	D67FAFE2
F7D91E80	C06F661D	C44BEC1E	7343619A	883C8A2B	4A087A92	D13036AD	D5BAFF11	89BF04CD	8D699289
FE312F98	73CD2D0B	54D5D3C6	60BC7828	49519108	B0B16768	9BBE2F20	69AC7F47	0784CD90	E6882A86
429DF00B	2A5A8051	3F0E6E0F	3FCAB5C0	DF79E0A0	62CA2C8A	D6BDF519	A1CA38AC	B8AE6888	D2D350DA
C390727D	29F39FFD	F8FD4896	4B7508AC	A81F760F	A1AB2BF2	91F310D4	9B28D382	AA827D1F	B5FECED2A
EBC136D3	BC5B42CB	9F0C7385	AD556F8E	BDA1E479	3896C4CE	D1F7006F	A72094CA	3228F88A	AF078661
1900D6B3	A1CA10AC	86F48CAB	73CBBC76	1DC707F6	4DD04366	37DE4D2E	0BBD19AA	66E1E736	A04C66A0
894C781D	022E1C39	58A4BD84	D6927D78	2F61A34E	723285F6	6372B575	7B705E4D	0EDB31F8	6D674617
C81AD319	52FA4E9B	E2CFEAC1	21BDD22	CF691251	1B647D9C	2F9CC063	509E3359	6E749D2A	53B947F3
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BC2ED413	C39D16A1	47B4514B	13570BF3	B887C38A	E1052459	EB327F4B	79EE0B90	02795C24	5D07251B
AE6CD0E2	308B9DC4	308D6C8B	AB4ECE1B	F059D46E	6C187141	6E3047B8	55B3417D	23968794	83AF92A6
2D9679DE	677C4AA6	92AC9229	D1F6A0A4	E1677CD6A	78D885F3	171EAE38	C727BF76	95270CB7	71FE6964
E5B28A6D	A71965A2	902B8B2F	7C766C69	D135C814	58F811C7	B61387E8	EA2FFF25	AEEEB544	FFB6B8B2

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DB51FC95 1A0F0DBD AABBD998 209276E3 D666ECC3 6A99E1C8 1E18F3CB 1E97E316 5665F8EC 78A5274B
CC3F0EC9 C074825C 001DC7EF 733C54D5 43226F9E 1CCC6B72 B1467F93 D9F3B99A 3EAA6F4F 48B1C659
CF646149 E59B1A4F D663735D BA5A59BF D87DD156 7FF49A63 037CBA61 99514B71 AF54A91D 8FC993A0
957BB730 CD276C69 85754924 C785B80F 02799C02 8271D0F5 654190BA F779BF97 7B517A58 69F84497
F1F67170 4930FB82 E6B751AB 559143D8 73653449 2612E6C4 C3ABEC0D EE3D20C1 E16D8B98 6E0DF0DF
2515AED5 553A6EF3 6FB4C8D5 A380C4B6 F48782CE D8A52BA7 F4E045F1 5B27505E 07405E5B 3B932669
19DF6FB3 E8E287A7 B879D11B 3BB692EB 665EF61A BA330D41 AAC1DC00 B9C1EC02 7A017CFD 8AB23D75
A05C19F3 2DB1C344 5CF4EAE7 345C3F5A C0D1FEB3 DA09986D A7325523 46A16A7C 0AEB6E33 64788399
FCB14253 00D12A42 A3FAD289 7AD78F4B FD868D5E 5FC8228D F225759A 0E93B125 E4C4FE9F C585E0E4
1C7E4990 F008CFC5 90E6EE8C E14255DC D38B8520 EC053969 01836AAA C7595685 B0E10A08 1A09DA00
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68E26CE5 F7A2D4C2 F6F60448 81C601AE 2736C0BE 27C40383 0292C11A 7DEFA9CB 273DFE36 DE7F8BD6
2707120E 3DBBB27 AD2D2D59 62D97158 B447B101 94A2F24B 72F90FC0 B89A5345 7E9035D4 6F08F7E8
7FCC6702 8053A1C4 A08E36B9 F7E57559 11A17732 89ADB78 763C7F17 4237CC1C 86FBAC95 4A09A27B
35E1774B 19EDBF9C F6CC2D0F 526B1B0A 4C574C7E 59A1F09B 572FD622 31AE1A1E C26C5C71 8C778CEB
ED7FDB75 485FC1F9 6C748620 7BC41A06 B594314C FB931475 254EF140 C4BE8B97 D52A5ED4 D235FE00
5CDECEAA 7030566E 83038ABA 2A5504F4 3E06ACFC 47333B86 DB3E96F3 50BA0CE1 F84ADFC0 0C820FFA
B44C4611 A6F14536 A9301A9C 47C12F73 7AF763EB 00166808 5F9E0C12 D8AF89A4 DC9B8DE0 94E1C87A
899EE498 FFFFF3CF 735130F9 F3F7EE97 11308713 D52A8A82 146F917A 9019AAF0 9D4E00CC 4ECFAE1C
855830FF 437CBAD4 BA741572 C07C7AC3 C62879EA 43743CE5 F8810D49 67982B3B 3B85382B ACC1BE7A
658872B2 C4C33E44 BAC96F4B 36B3DEAB C67334DC 48D17FA7 38328EC3 A74366CE C8D34C6 36A0641C
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39E820D4 E6B3CC64 3F758D55 A2D70A69 AF8914AE 1329EB88 69C7B7B0 B5389509 51D5C8D2 65084C8E
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61D54A7A 4688C4FF 700B96CD A352EA49 DFD8040E

Parameters: $n=24, h=10, w=16$

Private key:

00000200 00010203 04050607 08090A0B 0C0D0E0F 10111213 14151617 18191A1B 1C1D1E1F 20212223
24252627 28292A2B 2C2D2E2F BBF748C8 60784095 8C52DF9C DAA1F870 5DD8E4C8 7D3E54A8 30313233
34353637 38393A3B 3C3D3E3F 40414243 44454647

Public key:

00000013 BBF748C8 60784095 8C52DF9C DAA1F870 5DD8E4C8 7D3E54A8 30313233 34353637 38393A3B
3C3D3E3F 40414243 44454647

Message: 25

Signature:

00000200 3D46B21B 7171809B E5D5813A 8CB167CB 8B011E74 DEE49B01 B4B2F7F1 6E14E7C5 76941A5B
FFEA03CB A244AFAF E32ED739 02944738 D20FBE68 C681458D EF50CD58 F6163421 CC46DA94 4AF75824
33F69BB1 9147FEF5 ECDEE27C 19238831 7C349780 0B51A0CD 66DDB6D9 08708A1A BC64B880 27566A9D
839F7196 440147BA 3AB616CE C3D23DC2 9FDB40AB 54C15C72 A54EE0BA 2EA1672B 228EB63B E8AA8A66
944171E9 5CB4D9B6 522E732C A846883D A675C369 FDECB0DB 06B8368E 36040CA0 08434512 1A4FD90F
9E3DA8BF C6D05768 97C8655E 551022A5 CD8049D1 49C08A96 59DE4B47 DC89890C 04060BCC D81CD578
85919056 752F1551 3D8B44C1 C2675FEA 75048908 19B1A058 33565FD1 7C175EEA 42A3348C B3A17683
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F2FEC6CF E635737B E3E177A3 8116C5EE EFB211FE 4A216ED8 DB810892 8F807AC8 60FE5069 E943D5A9
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37E10CFF 26A2C10A B6E4F6E2 6C24329E E2DF2559 AAD94DE2 F76E5992 C31DEB28 FC403E0C 83796C94
457A82B5 F2FB04B5 2E51FE06 88727B51 5C3CE5E3 5E2E348FB 564DA012 FE07CE9A 2A4E9AF4 F8C24B7B
34E3217E 991B7063 54286BC7 98467B07 B5C443FB 73918B46 5503046A B521415E DC8AD493 FA748520
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27AE370C	A0DDC9CF	CF183D81	F8D8B977	4E0A1A6F	A1D05F10	B8C67822	99BD7563	8BD7A2A6	CE89FF59
3A55A2FA	A2484F81	3957204E	2C46A2B8	6EBA1467	D59FAAE2	7A674D1B	DAD5307A	1D26769E	38845433
5532D853	406CC7AF	F0DF4D83	1CF88DE5	DC832E21	7E1D269D	B7BF0CC5	53538071	9A47AC07	AF8D72AA
D20A19DE	F1B2E833	AFCCA7AB	3237704A	A708065B	808E7026	739BC748	24CB8C88	D4EA7E9C	7845C7AC
D7C13F1A	237059AA	E82CA915	785EA4D4	EFB00CD8	A5C95314	5FFD35C8	AECA1861	C42E6DFC	B898D6EA
724EACA0	FC6CDD72	221A418C	DCFC268E	4485BF26	FD3F11D1	A1D0C804	8CA4A2F1	5133AFBF	A5AD47AE
EBECD3F0	039AB901	F9AAC5FB	5C7F72EA	9621C669	4B39B500	B18E6AB8	37F49328	E548F4F6	363B5EBA
1D300922	B0956F3C	2F482BD1	2D74672E	B9FAFC84	75D46EA5	EE91D433	B8DF9BBE	ACF3EF4F	13E4B790
BFFFFBF7	6EF2D2ED	2BA4AA93	3EED53BF	FE11F705	7BF7A136	B887790D	5057AD04	23D6C6DC	7A8E6871
456C5EBA	D9C5F5C6	76BC7B6F	8CE06A9D	E1CB70E7	0702C6CD	CAB7E23D	EC7D1E4B	E22DC791	AD8EDE1F
FF6E45F5	02825B87	46D88522	7A51C65F	3D45976E	C5B8074B	696E8CA9	1C6230A3	B2B6D700	1DE648DC
E4C382D0	58E90546	29EF9D89	9446106B	55A3FE28	B7853FA7	D98F2BB0	2675C797	152C7B26	339FC088
004CC057	ECB1C6D5	52DD6956	CDC4BCF5	F800B2FD	91AC3A8B	E657672F	51558F63	2751AE1F	040883FF
F04F5ABA	CF3D010F	3A345FFC	BC617B32	3ECD A2CD	72643D4D	CF77C8C3	BD74631F	CFFE5F12	01C2B07C
203569B7	7DF05ABA	BEAC3415	F269663B	7004795F	5041D3AB	CA13DAFD	B74CA432	50E5AFEB	66651731
1267299D	4CB8AAC3	35584DF6	5AB5ABF2	04B46F7D	B86B80BA	1C566620	94574EF8	0562526C	CC5B1723
E49D83A2	ED4B7DF2	AD21A6BD	E11A84D1	6C9B200E	4EDDB8F1	2891ACB3	45B2716D	E786941C	C566EC9F
23800001	70EBDB5E	D8AF60EC	57177326	E5A5A923	F23D637C	6EB57ED3	D42CE069	1F5F724C	3E4D6A1A
AE341474	1CA370F5	B0F1FD22							

C.3 XMSS-MT

C.3.1 XMSS-MT SHA2-256

Parameters: $n=32, h=20, d=2, w=16$

Private key:

08000000	01020304	05060708	090A0B0C	0D0E0F10	11121314	15161718	191A1B1C	1D1E1F20	21222324
25262728	292A2B2C	2D2E2F30	31323334	35363738	393A3B3C	3E3F3F67	0E0C8CCA	74EB544D	358FABCE
89839FC7	3A6B89D1	A4E7D56B	4A45FCE9	6B20BD40	41424344	45464748	494A4B4C	4D4E4F50	51525354
55565758	595A5B5C	5D5E5F							

Public key:

00000001	670E0C8C	CA74EB54	4D358FAB	CE89839F	673A6B89	D1A4E7D5	6B4A45FC	E96B20BD	40414243
44454647	48494A4B	4C4D4E4F	50515253	54555657	58595A5B	5C5D5E5F			

Message: 25

Signature:

08000015	2CAFE9C8	71DC7677	DE8F9E9C	100A86D0	1D0D6F11	D971C66A	3AACFCDA	764F23AE	ED8E2076
1893346B	645CA534	A6F84512	351D23FE	CDF05EC5	464EC591	14B65D1E	E6F1B591	CBD83100	6E77ABD0
BAEC6007	81559667	5C208FFD	B0CFB245	2714451A	153C0743	CEA8AEB9	A5E6DB2D	7AB1A29B	B58AA64A
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431DA119	44C5E2A1	E11D81A8	DBEF3BF4	E60C3B67	549309B8	8744B271	F912401C	515C46B5	DAAF3914
6F593FA4	BF74C7C7	EC043399	A328056B	F3C4DB58	CD261D24	2E114890	DA0E978E	12B9B534	39F2025F
BEE8242E	9F6246E5	EC950445	B487CE8D	509CBAD1	FA1C401F	DA882BEF	05FC3DDC	6FA52546	112E9FFC
98B20743	B0A3CB69	358A884C	5BA1A5B4	3D4B11C4	E23785FD	F5A3F35C	818A8DF4	0EA60904	CC22D769
715027D0	BD2E81A7	3C375D07	9D1AECDE	CAEAE55A	3F2575F5	793E9465	DF1329CA	1FD82B27	4E8A7E69
08A3AEC3	179AC5BE	C058A119	19E5F8FA	F6A7165F	ABEC1561	F9E599E2	C4470E07	DAC66BFC	232D01B3
86BE65AD	9F1AF249	0A3EAB3E	568F49FD	C500D5A5	D03457AE	EB478707	58E3DAE4	65D48720	066B2D5B
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077E23AD	94B31506	3A5F38CE	B0237B08	421C41C7	8F043EF1	D735BE60	90D0CC6A	3BB58C52	E8195DD6
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944DAE74	EA450A75	32622EE3	D24D36A2	01A867AF	DA52B913	EDAE845B	C4F1D976	8A5C6ADF	E841662A
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34F8D2D3	8F8EF52B	B1201D9C	22AD945A	04B75EB8	40483892	FACB0C19	CAD40029	BC441CAA	D0E9B2E0
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CC02FCA3	08734977	4FE4CFC4	5B74B2D9	E775E691	13E1A399	A8BB5682	85AE64A6	2A9FC618	6CC7ED26
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7B8F9C7F	61B2E051	DC4D6E1B	AC4F6CF9	OCAA48C1	B4BB9E44	13AB400E	20651090	52AB0BD1	CCFDCC6B
16965E0A	2817C4D0	BBD911A9	1C83B22B	3282C9A0	2C9ADA87	9C197E17	C9A9DCBD	B6A08FC3	50A3C261
C0EFAB00	8A637E94	FBF1478D	D2FF28EE	8DCF40BB	C8D4222D	F3042F7E	C21E4A0B	675416EC	ADED4765
15A201B1	283C288B	FB09F68E	D58198C7	D27CF525	EC12AD57	11C16863	64A2E008	791423C0	7A195BCF

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F41213B1	A98F1EFD	3FE080B6	F6BE9B51	B037C8F2	0E45CD8C	1BB2251E	3C56F41E	4FD200CB	4A359662
42826D39	130237A1	0C3BE44E	8487F6EA	52AAA081	645FB369	4C9AE8B9	68DEA58C	6124AC7C	7194F62D
2B136298	333F798B	CB72A275	996F1B68	E53EE237	138FD7EF	3EEDE271	F45FCD04	E72AABCE	8B390D80
3D59838F	2E4F7F3E	4E0277C4	9C7E7F8D	EE5F6254	7F39D5E5	C7157B16	554934CD	458E47A3	D1A4637C
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5C1B99AC	CEC0E961	6CA6595D	E9FCF265	CC8102DC	4425D2BF	29AF47D8	C95C9928	38443B89	2C43A9BD
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ED647524	9A9EB4F8	A0E95AE9	7EE66814	63B7E9D8	25DF305D	6177B0F9	B77F3B64	03AB06C4	85F03564
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EA5A6545	ABCBD40D	EA610CF2	BE2B19B3	50F1D421	003A8958	BC5A3F39	C63B3F9E	FF67F9BD	AD5057B5
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784E06FF	E4A77502	E084DAB1	A5331CA7	E8728E83	BDF8A56B	2A8540A9	C202D2C2	5B4FCBA2	4523EB6C
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5A2B69D0	A7757E74	1C5B82E7	628A1DE7	824DCCC6	0C7D6EB8	A6A4780B	24ECF84A	19C933C0	19533611
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0C26BD64	2E8034AA	2D44E533	287F12F0	EAAB6CA0	6A8B913A	289A51C9	5FDA1038	5DF2B71F	BA42F770
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AC31FA39	B55C9F24	84F45626	3E5ED766	8EE0AA37	6527BF20	3313DABD	D1883264	22F0E860	B9E99CFF
BFFC650E	846BB60B	66014448	CE3928AE	5D5760D3	A747AC88	16FD4FCA	CF49D972	4D18D4A8	3480D73C
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DBA8B96E	DBC1E4FC	9FE04781	72E1BF9C	6DD3A248	598BA7AE	FB049751	9D879580	AF927F3A	645C4987
9470ABD6	0529D000	0066F523	836A03AB	6D5CB4A5	A82D3CE9	019F88A3	C929E77E	037061BF	66D95CE1
21B27E									

Parameters: $n=24, h=20, d=2, w=16$

Private key:

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25262728	292A2B2C	2D2E2F82	D4D48D76	4921D438	550FA2CE	EA616EF0	B5B8AB92	0ED62C30	31323334
35363738	393A3B3C	3D3E3F40	41424344	454647					

Public key:

00000021	82D4D48D	764921D4	38550FA2	CBEA616E	F0B5B8AB	920ED62C	30313233	34353637	38393A3B
3C3D3E3F	40414243	44454647							

Message: 25

Signature:

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943AA6FF	59666AC8	50C43997	2BE95C02	980E98D3	A9FF73D1	DD91414C	BB566E92	CCB0D6B1	D115F61F
58700817	F92C21BE	C9A5104B	58CC9713	9EA6E42E	176EA7BE	DFCF61B0	7F0ED365	BCC6188F	1C469E28
69F9E90F	6BFBD002	80E8736C	9064B70B	9AF5CD56	D2C58875	FA3199A0	01735D50	545A40CB	38439996
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B6BC17E9	50510A1E	5315BF97	267C633E	AE94B48E	F265A41A	D5D8B49B	66FC69DC	D4363388	47E484A8
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5039430D	79384D08	9E70C361	3DC415CB	F38DDFCE	93649E0F	DF9A733B	7AB2AC7C	448F4CDA	92E80779
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425B88E2	C5F5E58F	487977DB	8216A72C	74B184D7	E6B2F678	AACF7389	0E2FD40A	84506555	6BF91D96
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9CD951D1	584ABF96	B831836B	5D93CFDF	DB00B60B	DBE4C0AD	648DB013	877E90FB	4C97EA80	5AD4C19D
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B8F25393	F376F0AF	DB87534D	981A7891	4EF39D94	DF82681A	C28D79BA	56C21677	AC714432	17CE8B7F
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BED836EA	53074560	480D83F0	49E80029	0CB48F97	7C68730F	FFB9FC8F	110BE035	89419520	159DEC27
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327387C7	5496997E	5E0423B5	F03C494F	5A9FCDC2	34385D14	71B831A2	F422D6DE	7AA09325	8995B4B6

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9B2546B5	1293ED0B	6FF19D3E	ABB94721	8E8EE391	F9FED4E1	1E7A7FE2	81EC6A51	63F069D8	B41325D0
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D9368161	3490864D	C6F02E1F	0E2A2165	87DF2502	846BD66B	91BBF6A0	EF75B755	AA9DFD	

C.3.2 XMSS-MT SHAKE

Parameters: $n=32, h=20, d=2, w=16$

Private key:

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9E558303	8835804D	9F540A7C	A9039F8C	40FEB440	41424344	45464748	494A4B4C	4D4E4F50	51525354
55565758	595A5B5C	5D5E5F							

Public key:

00000029	69C006C5	D6BE4B38	294DE9EF	AB9E5583	03883580	4D9F540A	7CA9039F	8C40FEB4	40414243
44454647	48494A4B	4C4D4E4F	50515253	54555657	58595A5B	5C5D5E5F			

Message: 25

Signature:

080000BA	FCEBCB9E	55ECB1A3	4AE795C7	4BC20311	D62A6F4A	38D7EAAC	027EF5FD	C974C334	C77F278C
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Parameters: n=24, h=20, d=2, w=16

Private key:

08000000 01020304 05060708 090A0B0C 0D0E0F10 11121314 15161718 191A1B1C 1D1E1F20 21222324
25262728 292A2B2C 2D2E2F70 1B02B281 ACB7F8E0 82098C35 9E2BB987 3D7B3603 41F12D30 31323334
35363738 393A3B3C 3D3E3F40 41424344 454647

Public key:

00000031 701B02B2 81ACB7F8 E082098C 359E2BB9 873D7B36 0341F12D 30313233 34353637 38393A3B
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Message: 25

Signature:

080000E0 199594BE AC866B26 FA250A5F DE4028EC 2BABEAB5 8CCBA382 11005D0D 265FABDC 95ECD4D7
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6F45ED4D	EA2AD7E4	AE041FCF	6457F5C5	90CA0CD4	411E3E7C	CFC02E07	655F0F5C	583C5F11	F76A9D72
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CBAAB6D7	8FAB2DA0	94A9E53D	22F86050	349F63C0	463A461A	D3C0F78F	843753CC	E5FA184B	D76325DC

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6062A8B8 3F00BEC1 1051A32D 8D088811 70D9D4A5 60E7BDF A C99EDE0A A9AEFA18 C2D7F5

C.4 LMS

C.4.1 LMS SHA2-256

Parameters: $n=32, h=10, W=4$

Private key:

00000000 00000000 00000006 00000003 0F0E0D0C 0B0A0908 07060504 03020100 2F2E2D2C 2B2A2928
27262524 23222120 1F1E1D1C 1B1A1918 17161514 13121110

Public key:

00000006 00000003 0F0E0D0C 0B0A0908 07060504 03020100 A7CD5F57 42C84B1C B5790917 D10DA7FD
4435ED69 F8D5951E 3DEA3606 02F488AE

Message: 25

Signature:

00000000 00000003 7AD25F69 6309A956 A00CFA31 53016A62 3B27DAC3 144795AC 75A82ACC 94FFB0B6
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