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(54) SIGNATURE VERIFICATIONS USING MERKLE SIGNATURE SCHEMES

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H04L 9/32 (2006.01)

(52) **U.S. Cl.**
CPC ***H04L 9/3247*** (2013.01); ***H04L 9/3239*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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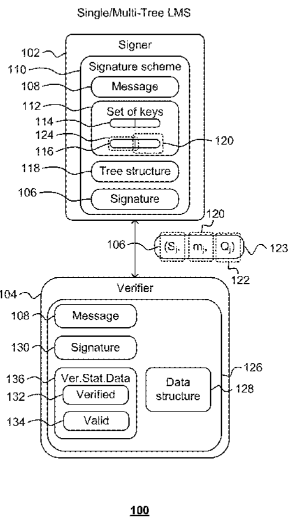
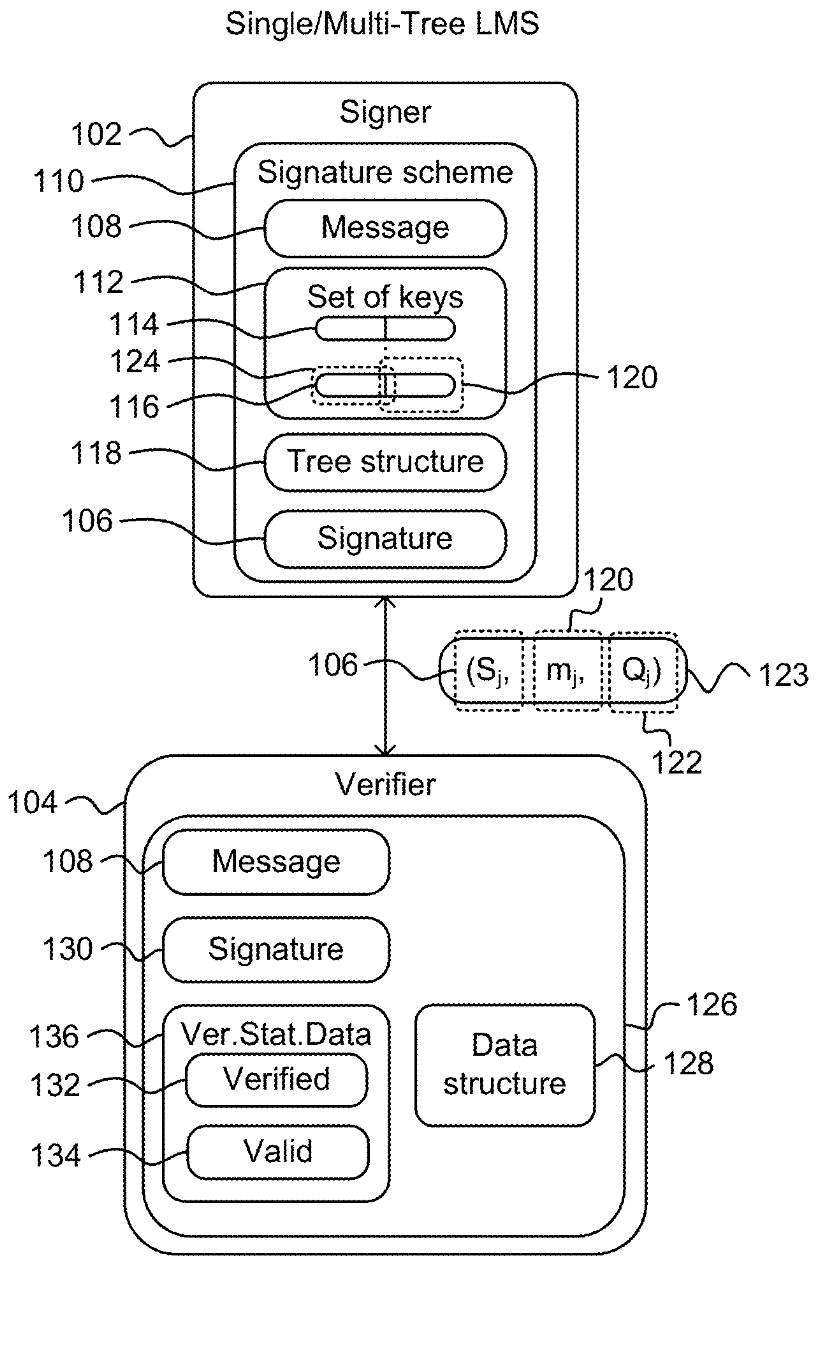
(57) ABSTRACT

Examples relate to machine readable storage storing instructions arranged, when processed, to realise methods of verifying as valid a received signature, associated with a respective received message, generated using a Merkle Signature Scheme comprising a Merkle Tree, the Merkel Tree comprising a root node, a number of leaf nodes and a number of intermediate nodes disposed between the root node and the leaf nodes; the instructions comprising instructions to:
calculate a hash value in response to receiving the respective message;
determine that the calculated hash value corresponds to a stored previously verified hash value
calculated in response to a previously received message, and
verify the received signature as valid based on the stored previously verified hash value.

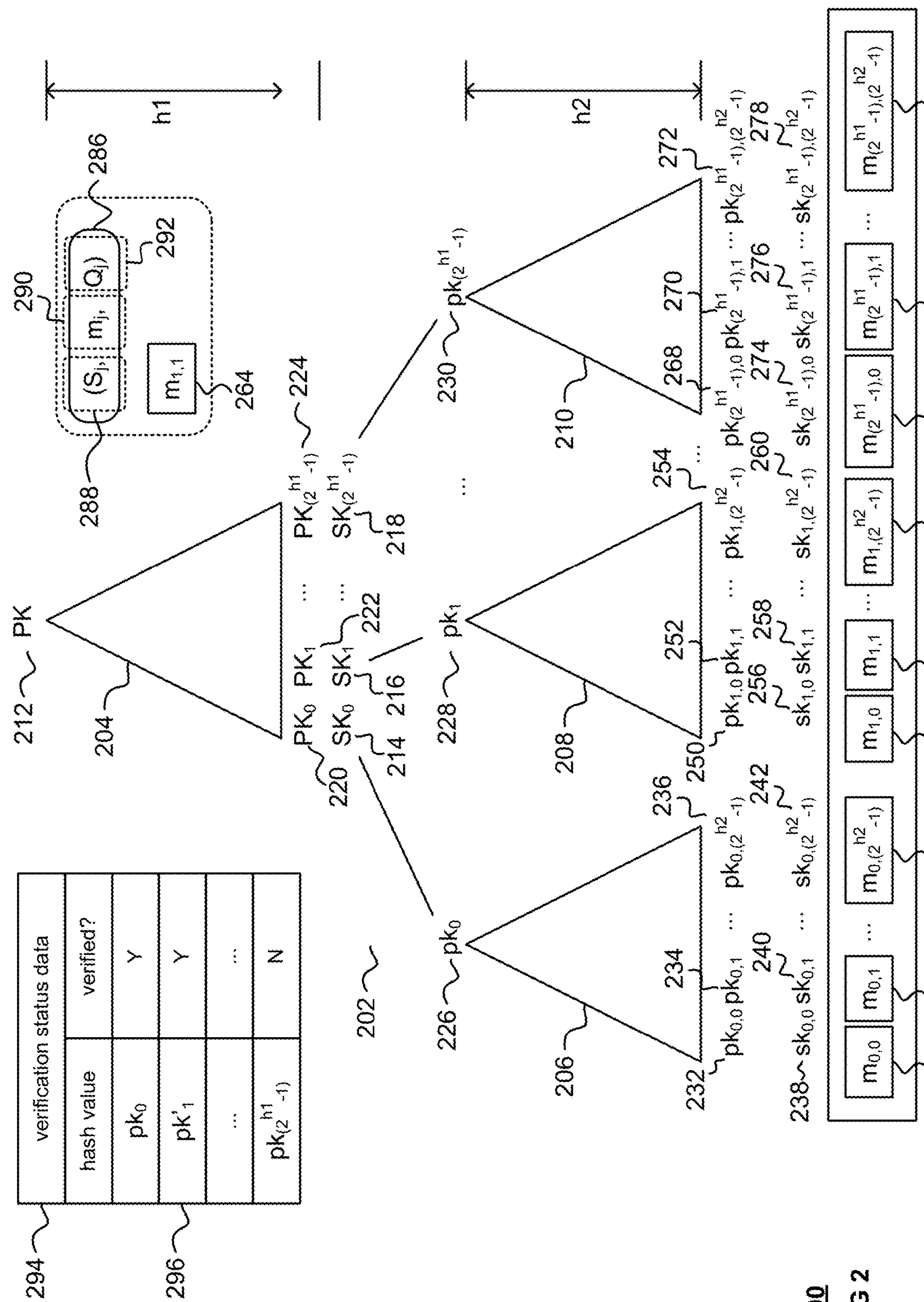
15 Claims, 5 Drawing Sheets




Single/Multi-Tree LMS
Signer
102
Signature scheme
110
Message
108
Set of keys
112
114
124
116
120
Tree structure
118
Signature
106
120
106
$(S_j,$
$m_j,$
$Q_j)$
123
122
Verifier
104
Message
108
Signature
130
Ver.Stat.Data
136
Verified
132
Valid
134
Data structure
126
128

100

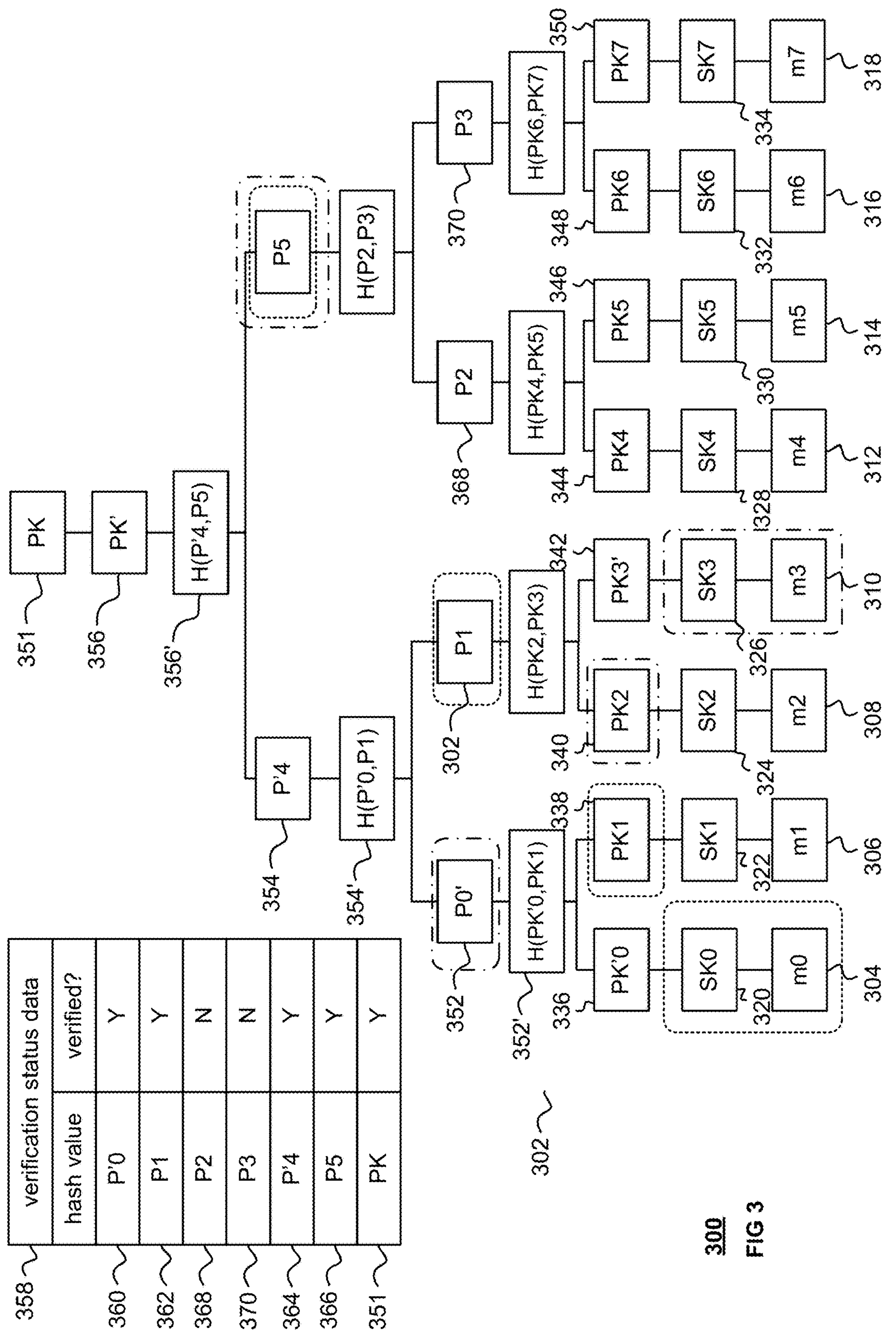
FIG 1


PK
212
204
PK_0 PK_1 ... $PK_{(2^{h1}-1)}$
SK_0 SK_1 ... $SK_{(2^{h1}-1)}$
220 214 216 222 218 224
h1
h2
202
pk_0 226
pk_1 228
$pk_{(2^{h1}-1)}$ 230
206 208 210
$pk_{0,0}$ $pk_{0,1}$ ... $pk_{0,(2^{h2}-1)}$
$sk_{0,0}$ $sk_{0,1}$ ... $sk_{0,(2^{h2}-1)}$
232 234 236 238 240 242
$pk_{1,0}$ $pk_{1,1}$ ... $pk_{1,(2^{h2}-1)}$
$sk_{1,0}$ $sk_{1,1}$ ... $sk_{1,(2^{h2}-1)}$
250 252 254 256 258 260
$pk_{(2^{h1}-1),0}$ $pk_{(2^{h1}-1),1}$ ... $pk_{(2^{h1}-1),(2^{h2}-1)}$
$sk_{(2^{h1}-1),0}$ $sk_{(2^{h1}-1),1}$ ... $sk_{(2^{h1}-1),(2^{h2}-1)}$
268 270 272 274 276 278
$m_{0,0}$ $m_{0,1}$ ... $m_{0,(2^{h2}-1)}$ $m_{1,0}$ $m_{1,1}$ ... $m_{1,(2^{h2}-1)}$ $m_{(2^{h1}-1),0}$ $m_{(2^{h1}-1),1}$ ... $m_{(2^{h1}-1),(2^{h2}-1)}$
244 246 248 262 264 266 280 282 284
$(S_j,$ $m_j,$ $Q_j)$
$m_{1,1}$
288 290 286 292 264
294 296

verification status data	
hash value	verified?
pk_0	Y
pk'_1	Y
...	...
$pk_{(2^{h1}-1)}$	N

200

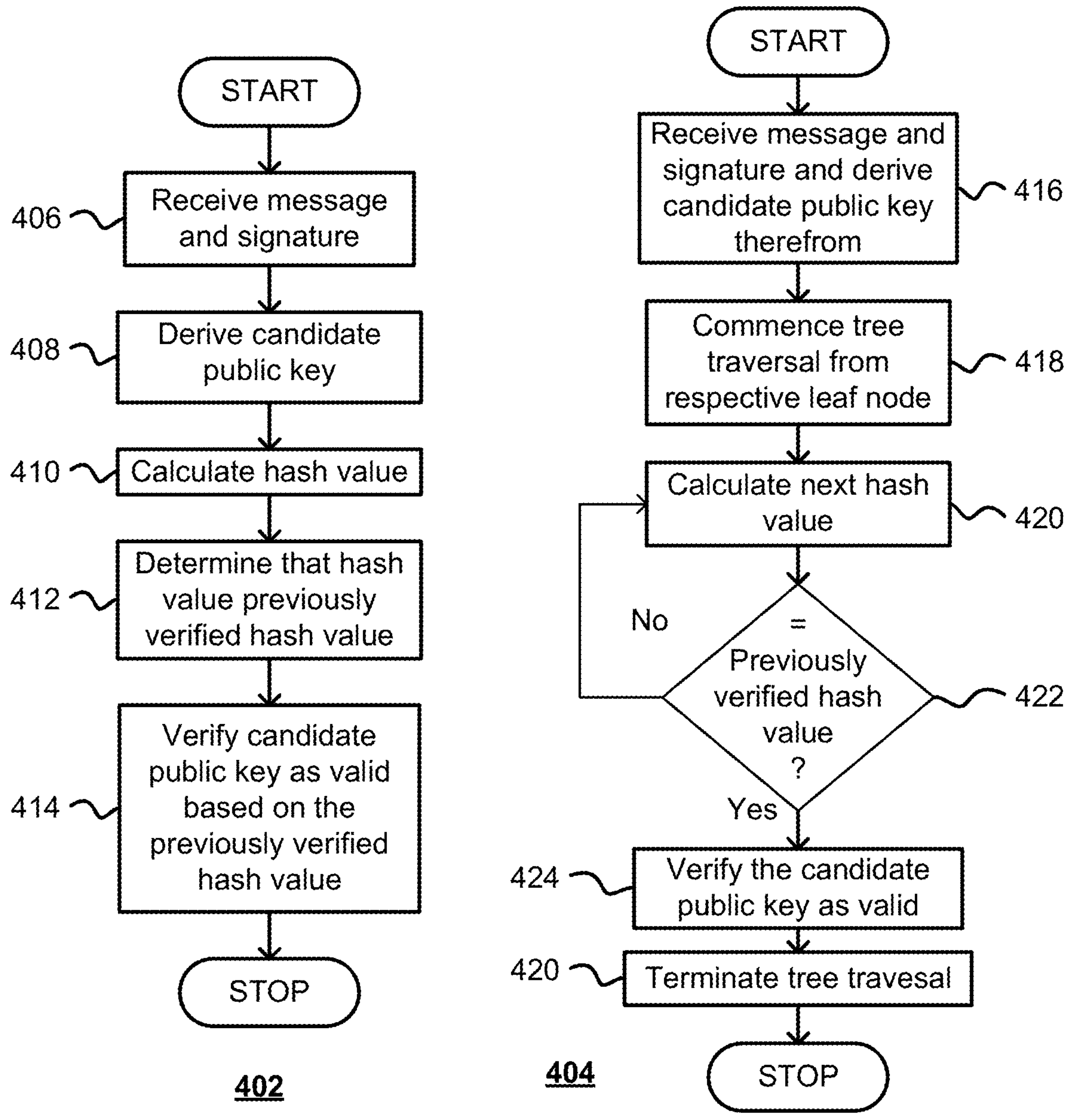
FIG 2



verification status data	
hash value	verified?
P'0	Y
P1	Y
P2	N
P3	N
P'4	Y
P5	Y
PK	Y

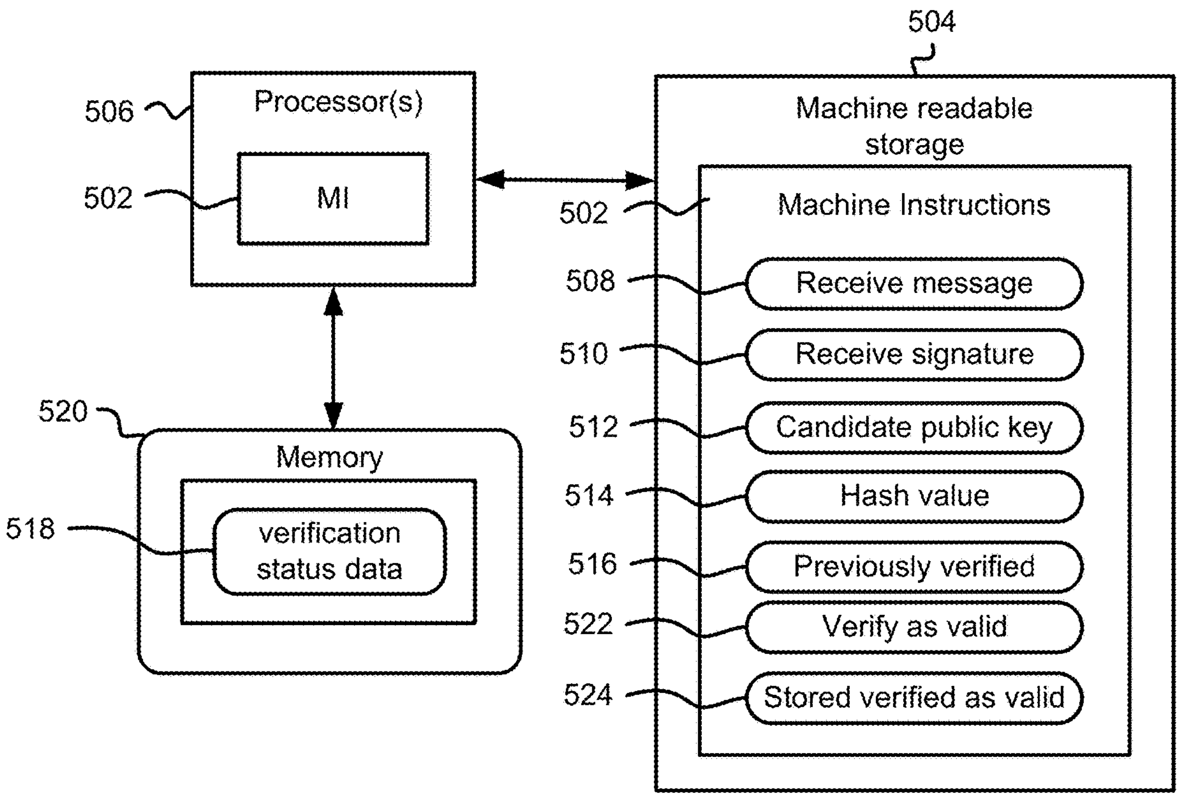
300

FIG 3


START
406
Receive message and signature
408
Derive candidate public key
410
Calculate hash value
412
Determine that hash value previously verified hash value
414
Verify candidate public key as valid based on the previously verified hash value
STOP
402
START
Receive message and signature and derive candidate public key therefrom
416
Commence tree traversal from respective leaf node
418
Calculate next hash value
420
No
= Previously verified hash value ?
422
Yes
424
Verify the candidate public key as valid
420
Terminate tree travesal
404
STOP

400

FIG 4


504
Machine readable storage
502
Machine Instructions
508
Receive message
510
Receive signature
512
Candidate public key
514
Hash value
516
Previously verified
522
Verify as valid
524
Stored verified as valid
506
Processor(s)
502
MI
520
Memory
518
verification status data

500

FIG 5

SIGNATURE VERIFICATIONS USING MERKLE SIGNATURE SCHEMES

BACKGROUND

A stateful hash-based signature scheme (HBSS) is a quantum secure signature scheme that provides integrity and data origin authentication on a message even if an attacker has a quantum computer. It is a digital signature scheme that uses a public-private key pair in which the key pair can be used to sign only a fixed number of messages where the upper bound is defined prior to key generation and requires the signer to maintain a state. The computational overhead associated with verifying messages under an HBSS can be significant.

BRIEF INTRODUCTION OF THE DRAWINGS

Examples will be described with reference to the accompanying drawings in which

FIG. **1** shows an example cryptographic system comprising a signer and a verifier according to an example;

FIG. **2** illustrates a multi-tree Merkle tree and associated verification status data structure to verify a candidate public key according to an example;

FIG. **3** depicts a single tree Merkel tree and associated verification status data structure to verify a candidate public key according to an example;

FIG. **4** illustrates a pair of flowcharts for verifying a candidate public key according to examples; and

FIG. **5** illustrates machine readable storage storing machine readable instructions to verify a candidate public key according to an example.

DETAILED DESCRIPTION

HBBSs use Merkle trees in verifying whether or not a received message and signature are valid. That verification uses significant computational resources to determine if a candidate public key derived from a received message and signature is valid by calculating an overall root node hash value from that candidate public key and verifying if the overall root node is the same as the previously received public key corresponding to the root node. Calculating the candidate public key is computationally resource intensive. Furthermore, the number of calculations performed in verifying a candidate public key increases with Merkle tree height. The number of calculations also increases with sub-tree height as well as with the number of subtrees if the HBSS uses a multi-tree Merkle tree. Examples below demonstrate that a significant reduction in the number of computations used to verify a candidate public key can be realised.

FIG. **1** illustrates a schematic view of an example cryptographic system **100**. The cryptographic system **100** comprises a signer **102** and a verifier **104**.

The signer **102** is arranged to generate a signature **106** associated with a respective message **108** using a hash based digital signature scheme **110**. The signature **106** is generated using a key selected from a set of one-time-signature (OTS) keys **112**. Examples can be realised in which the OTS can be generated from a seed. The seed can be a single seed. The set of keys **112** comprises a plurality of public-private key pairs **114** to **116**. The set **112** of keys is associated with a tree structure **118**. The tree structure **118** can comprise a multi-tree Merkle tree or a single tree Merkle tree. Such a

multi-tree Merkle tree is described below with reference to FIG. **2**. Such a single tree Merkle tree is described below with reference to FIG. **3**.

The signer **102** is arranged to send the signature **106** to the verifier **104** together with a message **120** and authentication path data **122** as a tuple **123**. The signer **102**, or other entity, can also send a public key **121** to the verifier **104**. Alternatively, the verifier **104** can be arranged to have already received or have stored a set of public keys corresponding to the set of keys **112**. The public key **121** corresponds to a private key **124**, such as, for example, one of the OTS keys, used to sign the message **108**. The authentication path data **122** is associated with hash values within the data structure **118** useful for verifying the signature **106**. The authentication path data **120** can represent pairs of hash values and respective nodes within the tree structure or indices associated with respective nodes within the tree structure **116**. The hash based digital signature scheme **110** can comprise at least one of: an XMSS: eXtended Merkle Signature Scheme, as established by RFC8391.txt, ISSN: 2070-1721, May 2018, a Leighton-Micali Hash-Based Signatures, as established by RFC8554, ISSN: 2070-1721, April 2019, a Hash-based Signature Schemes as detailed in NIST Special Publication 800-208, October 2020, or any other Merkle hash tree or Hash-Based Signature Scheme, taken jointly and severally in any and all permutations.

Examples will be described in which the signer **102** sends the public keys to the verifier **104**. However, examples can be realised in which the verifier **104** has previously received the public keys from the signer **102**, or other entity, or in which the verifier **104** was deployed with the public keys having already been embedded within, or otherwise being accessible to, the verifier **104**.

The verifier **104** is arranged to verify the received signature **106** using a verification process **126**. The verification process **126** is a Merkle tree verification scheme as detailed in the above RFCs. The verification process **126** uses the received tuple **123** comprising the signature **106**, the message **121** and the authentication path data **122** to generate a candidate public key **120'**, in particular, the signature **106** and the message **121** are used to generate the candidate public key that is subsequently verified, if valid, by comparing generated hash values with previous hash values that have been verified as valid. The previous verified hash values **132** can comprise at least one, or more than one, previously calculated or previously received hash value that has been verified by the verifier **104** as valid. The previously calculated or received hash value that has been verified by the verifier **104** as valid can comprise at least one, or more than one, of the set comprising: a hash value associated with a node of a single tree Merkle tree or a node of a multi-tree Merkle tree, an overall root node hash value associated with the overall root node of a multi-tree Merkle tree, a root node hash value associated with a root node of a sub-tree of a multi-tree Merkel tree, a root node hash value associated with the root node of a single tree Merkle tree, or a hash value of a multi-tree single tree Merkle tree, taken jointly and severally in any and all permutations. When the candidate public key **102'** has been verified as valid, the corresponding signature **106** can also be deemed to be verified as valid. Furthermore, in response to determining that a hash value is valid, that is, has been verified as valid, at least an indication **134** of at least that validity is stored within a verification status data structure **136**.

An example of an implementation of the verification process **126** will be described with reference to FIG. **2**.

FIG. **2** depicts a view **200** of a multi-tree Merkel tree **202**. The Merkle tree **202** is an example of the above-described tree structure **118**. The Merkel tree **202** comprises a number of sub-trees **204** to **210**. Each sub-tree comprises a respective root node, a number of leaf nodes, and a number of intermediate nodes disposed between the root node and the leaf nodes. An intermediate node is an example of an interior node as specified in RFC8554. Each sub-tree has a respective height that is defined as the distance between a root node and the leaf nodes. In the example depicted in FIG. **2**, the height of the highest sub-tree **204** is h1 and the height of the lowest level sub-trees **206** to **210** is h2. Examples can be realised in which h1 and h2 have different values or the same value.

The sub-trees **204** to **210** can be binary sub-trees. In general, a Merkle tree-based signature scheme of height hç $\mathbb{Z}$, which is defined as the distance between the root node and the leaf nodes of the tree, comprises 2^h leaf nodes and $2^{h+1}-1$ nodes in total, which, in conjunction with a one-way hash function, H(x,y), extends a one-time signature scheme to 2^h signable messages for each public key, that is, for each root node.

Therefore, given the height h1 of the highest sub-tree **204**, the highest sub-tree **204** comprises $L=2^{h1}$ leaf nodes and a total of $N=2^{h1+1}-1$ nodes. Similarly, the lowest level sub-trees **206** to **210**, given the respective heights h2, comprise 2^{h2} leaf nodes and a total of $2^{h2+1}-1$ nodes.

The highest-level sub-tree **204** comprises a root node **212**, which is known as the overall root node in a multi-tree Merkle tree. The root node **212** has an associated overall public key, PK. The overall public key, PK, is calculated as a hash of two immediate child nodes (not shown). The highest-level sub-tree **204** also comprises a plurality public keys $PK_0, PK_1, \ldots, PK_{(2^{h1}-1)}$ **220** to **224**. Each public key $PK_0, PK_1, \ldots, PK_{(2^{h1}-1)}$ **220** to **224** has a corresponding private key $SK_0, SK_1, \ldots, SK_{(2^{h1}-1)}$ **214** to **218**. The private and public keys **214** to **224** are used to sign and verify messages. The messages that are signed by the private keys $SK_0, SK_1, \ldots, SK_{(2^{h1}-1)}$ **214** to **218** are respective public keys $pk_0, pk_1, \ldots, pk_{(2^{h1}-1)}$ **226** to **230** associated with respective root nodes of the sub-trees **206** to **210**. Each public key of the public keys $pk_0, pk_1, \ldots, pk_{(2^{h1}-1)}$ **226** to **230** is derived from two associated child hash values (not shown) associated with child nodes (node shown) of the root nodes (not shown).

The lower-level sub-trees **206** to **210** comprise root nodes that have respective root node hash values, respective leaf nodes that have at least one, or both, of respective public keys or hash values of such respective public keys, and respective intermediate nodes that have respective hash values. Each node, other than a leaf node, derives its respective hash value from a pair of child nodes of the intermediate nodes and leaf nodes.

Therefore, the left-most sub-tree **206** depicted in FIG. **2** comprises the above-mentioned public key pk_0 **226**, a plurality of intermediate nodes, and 2^{h2} leaf nodes. The leaf nodes have corresponding public keys $pk_{0,0}, pk_{0,1}, \ldots, pk_{0,(2^{h2}-1)}$ **232** to **236**. Each public key of the public keys $pk_{0,0}, pk_{0,1}, \ldots, pk_{0,(2^{h2}-1)}$ **232** to **236** has a corresponding private key $sk_{0,0}, sk_{0,1}, \ldots, sk_{0,(2^{h2}-1)}$ **238** to **242**. The public keys $pk_{0,0}, pk_{0,1}, \ldots, pk_{0,(2^{h2}-1)}$ **232** to **236** and private key $sk_{0,0}, sk_{0,1}, \ldots, sk_{0,(2^{h2}-1)}$ **238** to **242** are used to verify and sign respective messages **242** to **248**.

It will be appreciated that verification can use more than merely a message, a corresponding signature, and a respective candidate key. The example presented is a simplified example for explanation purposes. However, examples can

be realised that use other information as part of the verification. Examples can be realised that also use one or more than one of the following, taken jointly and severally in any and all permutations: a security string that is distinct for each invocation comprising the set of fields {l,r,q,D,l,j,C}, as specified in RFC8554, section 7.1. Similarly, although examples have been described with reference to a signature being generated from a message and the next OTS, examples can also use other information. For example, a Leighton-Micali Hash-based Signature (LMS) can comprise: the number q of the leaf associated with a LM-OTS, a typecode indicating a respective LMS algorithm, an array of h m-byte values associated with a respective authentication path through the tree from the leaf associated with the OTS to the overall root of the tree **202**. Furthermore, it will be appreciated that a signature can comprise a number of parameters. The number of parameters can comprise, for example, for an LMS signature, the parameters h: representing the height of the tree, m: representing the number of bytes associated with each node, and H: representing a second-preimage-resistant cryptographic hash function that accepts byte strings of any length and returns an m-byte string, as specified in section 5.1 of RFC8554. Examples can be realised in which such parameters or other information are used consistently throughout the whole tree. However, alternative examples can be realised in which each subtree has a respective set of parameters or other information. The respective sets can be different to one another, be common to one or more than one subset of subtrees with each subset of subtrees having respective common sets of parameters or other information.

The second left-most sub-tree **208** depicted in FIG. **2** comprises the above-mentioned public key pk_1 **228**, a plurality of intermediate nodes, and 2^{h2} leaf nodes. The leaf nodes have corresponding public keys $pk_{1,0}, pk_{1,1}, \ldots, pk_{1,(2^{h2}-1)}$ **250** to **254**. Each public key of the public keys $pk_{1,0}, pk_{1,1}, \ldots, pk_{1,(2^{h2}-1)}$ **250** to **254** has a corresponding private key $sk_{1,0}, sk_{1,1}, \ldots, sk_{1,(2^{h2}-1)}$ **256** to **260**. The public keys $pk_{1,0}, pk_{1,1}, \ldots, pk_{1,(2^{h1}-1)}$ **250** to **254** and the private key skim, $sk_{1,0}, sk_{1,1}, \ldots, sk_{1,(2^{h2}-1)}$ **256** to **260** are used to verify and sign respective messages **262** to **266**.

The above applies to each remaining sub-tree (not shown) culminating in the right-most sub-tree **210**. The right-most sub-tree **210** depicted in FIG. **2** comprises the above-mentioned public key $pk_{1,(2^{h1}-1)}$ **230**, a plurality of intermediate nodes, and 2^{h2} leaf nodes. The leaf nodes have corresponding public keys $pk_{(2^{h1}-1),0}, pk_{(2^{h1}-1),1}, \ldots, pk_{(2^{h1}-1),(2^{h}2-1)}$ **268** to **272**. Each public key of the public keys $pk_{(2^{h1}-1),0}, pk_{(2^{h1}-1),1}, \ldots, pk_{(2^{h1}-1),(2^{h}2-1)}$ **268** to **272** has a corresponding private key $sk_{(2^{h1}-1),0}, sk_{(2^{h1}-1),1}, \ldots, sk_{(2^{h1}-1),(2^{h}2-1)}$ **274** to **278**. The public keys $pk_{(2^{h1}-1),0}, pk_{(2^{h1}-1),1}, \ldots, pk_{(2^{h1}-1),(2^{h}2-1)}$ **268** to **272** and private key $sk_{(2^{h1}-1),0}, sk_{(2^{h1}-1),1}, \ldots, sk_{(2^{h1}-1),(2^{h}2-1)}$ **274** to **278** are used to verify and sign respective messages **280** to **284**.

The messages **224** to **248**, **262** to **266** and **280** to **284** can form part of a larger overall message or data set. For example, the messages **224** to **248**, **262** to **266** and **280** to **284** can form, or be associated with or otherwise derived from, respective portions of software **286**. The software **286** is an example of machine-readable code. Each portion of the software **286** is an example of a portion of data associated with the code.

Although the examples described herein refer to the message or a message, examples can be realised that use or refer to a message representation or the message representation such that a message is input into a signature algorithm that computes a message representation from the message and computes any signatures based on the message representation rather than directly from the message. A verifier in such as arrangement would compute the converse. Accordingly, any of the examples described herein can use such a message representation instead of a message.

Assume that the tree **202** is a two-level tree. Although an example will be described with reference to the tree being a two-level tree, examples can be realised in which the tree **202** has at least two or more levels. The private keys **238** to **242**, **256** to **260**, **274** to **278** are used to sign respective messages **224** to **248**, **262** to **266** and **280** to **284**. The public keys are used to populate the tree with respective hash values. Each hash value of a parent node is generated from a pair of hash values; one from each child node of two child nodes in the case of a binary tree. The initial hash values of the leaf nodes are generated from hash values associated with pairs of the public keys **232** to **236**, **250** to **254**, **268** to **272**. The hash values are calculated for each level within each subtree, and for each subtree, until the subtree is fully populated hash values and respective root node hash values **212**, **226** to **230**. The overall root node hash value **212** is sent to the verifier **104** for using in verifying the messages **244** to **248**, **262** to **266**, **280** to **284** sent to the verifier in due course.

Assume that the message $m_{1,1}$ **264** is to be sent to the verifier **104**. A signature corresponding to the message is generated. In the case of a multi-level Merkle tree, the signature comprises as many One-time-signatures (OTS) as there are levels in the tree. In the present example, the signature comprises two OTS. The two OTS comprise: one OTS on the message $m_{1,1}$ **264** and one OTS on the root node hash value, that is, the public key pk_1 **228** of the corresponding sub-tree **208**. Although the example has been described with reference to a simple public key, examples can be realised in which the public key comprises the root node hash value together with other parameters such as, for example, one or more than one parameter taken from the set of {l, h, w, q} taken jointly and severally in any and all permutations, where l is a 16-byte string that indicates which Merkle tree with which a OTS is used, h is the height of a Merkle tree, w is the Winternitz parameter, and q is a 32-bit integer that indicates the leaf of the Merkle tree where the OTS public key appears. Examples can be realised in which any of the public keys comprises a hash value together with other parameters. For instance, in respect of a tree or sub-tree, examples can be realised in which the public key comprises a root node hash value together with other parameters such as any parameters of the set {l, h, w, q, n, p, ls, m} taken jointly and severally in any and all permutations; the parameters {l, h, w, q, n, p, ls, m} are defined in RFC8554 in, for example section 4.1, where n is the number of byte of the output of the hash function, w is the width in bits of the Winternitz coefficients, that is, the number of bits from the hash value or checksum that i used with a single Winternitz chains, and it a member of the set {1,2,4,8}, p is the number of n-byte string elements that make up an LM-OTS signature, ls is the number of left-shift bits used in the check sim function Cksm, and H is a second-preimage-resistant cryptographic hash function that accepts byte strings of any length and return an n-byte or m-byte string, l is a 16-byte string that indicates which Merkle tree this LM-OTS is used with, p is a 32-bti integer that indicates the leaf of the Merkle tree where the OTS public key appears, h is the height of the tree, m is the number of bytes associated with each node. Any of the examples can be realised in which the public keys are LMS public keys that comprises one or more than one of the following elements: an LMS parameter set, an LM-OTS parameter set, the random value l and the hash value of the root node, which is defined as K in sections 4.1 and 4.3 of RFC8554, all taken jointly and severally in any and all permutations.

The private key $sk_{1,1}$ **258** is used to sign the message $m_{1,1}$ **264** to generate a OTS on the message $m_{1,1}$ **264**, which gives a signature of $\mathrm{Sig}_{sk_{1,1}}(m_{1,1})$ The private key SK_1 is used to sign the root node hash value pk_1 **228** to generate the OTS on the root node hash value pk_1 **228**, which gives $\mathrm{Sig}_{SK_1}(pk_1)$. An overall signature $\mathrm{Sig}_{sk_{1,1}}(m_{1,1}),pk_{1,1},\mathrm{Sig}_{SK_1}(pk_1)$, PK_1 **286** comprising the OTS **288**, the corresponding public keys **290** and associated authentication path data **292** is generated and sent to the verifier **104** as a tuple **288**. The tuple **288** is an example of the above-described tuple **123**. The authentication path data **292** comprises hash values associated with selected nodes of the multi-tree that are used in verifying the overall signature **286** as valid. The overall signature **286** and corresponding message $m_{1,1}$ **264** are sent to the verifier **104**.

The same data structure **202** is constructed at the verifier **104** and used to verify any received signatures, and, in turn, authenticate any received respective messages of the messages **244** to **248**, **262** to **266**, **280** to **284**. For brevity, FIG. **2** will also be used to describe operations at the verifier **104** rather than using an additional separate figure specifically for verifier **104**. Therefore, also shown in FIG. **2** is a data structure **294** that is used by the verifier **104** to store an indication of whether or not any hash values have been verified. Examples of hash values that have been verified can comprise, for example, any one or more of: any verified hash values of the subtree root node hash values **226** to **230**, any verified hash values of any intermediate node hash values and the overall root node hash value, taken jointly and severally in any and all permutations. Again, as indicated above, although the example has been described with reference to using the overall root node hash value, examples can be realised in which the full public key is used, which comprises the overall root node hash value together with one or more than one parameter. Although the data structure **294** has been depicted separately from the multi-tree Merkle tree **202**, examples can be realised in which the information stored within the data structure **294** is stored as part of the multi-tree Merkle tree **202**. The data structure **294** is an example of the above-described data structure **136**.

An example will be described with reference to FIG. **2** in which sub-tree root node verified hash values are stored in the data structure **294**.

The verifier **104** receives the overall signature **286** and corresponding message $m_{1,1}$ **264**. The verification process **126** commences traversing the tree **202** calculating hash values from node pairs governed, or otherwise associated with, the authentication path data **292**. The traversal is performed bottom-up starting with the leaf node corresponding to a candidate public key $pk_{1,1}$ **252** associated with the first OTS. Each time a hash value is calculated, or for selected hash values (such as those corresponding to root nodes, or some other nodes), a determination is made, from the data structure **294**, regarding whether or not the calculated hash value corresponding to a given node has been previously verified as valid. Traversing the tree **202** calculating hash values continues until a calculated hash value is determined from the data structure **294** to have been previously verified as valid. If a calculated hash value is determined to have a corresponding verified hash value stored within the data structure **294**, traversing the tree is terminated insofar as concerns the current message $m_{1,1}$ **264** and the signature associated with that message is deemed to be verified as valid, which, in turn, results in the message $m_{1,1}$ **264** being considered to be authentic or authenticated.

It will be appreciated that depending on the message received, the traversal process could continue and culminate in calculating the overall hash value **212** of the overall root node of the upper-most tree **204**. However, for signatures associated with private keys associated with the same subtree, the traversal will continue until a previously verified root node of that subtree is encountered within the data structure **294**. An initial signature of a subtree generated using an initial private key of that subtree will result in the root node hash value being calculated and being eventually verified as valid.

Therefore, traversing the tree **202** continues until a root node hash value is encountered that has been previously verified as valid. That root node that has been previously verified as valid can be associated with the same subtree associated with a current message such as, for example, message $m_{1,1}$ **264**, or can be associated with a subtree of a higher level in the multi-tree Merkle tree **202**. Determining that a calculated hash value has been previously verified as valid avoids having to perform verification of OTS signatures or hash value calculations associated with higher nodes, that is, nodes more proximal to the overall root node, which can result in a considerable computational saving compared to calculating all hash values of nodes associated with a leaf node and a respective authentication path culminating the overall root node hash value. Therefore, terminating traversing and calculating such hash values on encountering a previously verified hash value reduces the computational overhead associated with verifying a received signature and, in turn, associated with authenticating a received message. The foregoing also reduces power consumption due to the reduced computational overhead.

Examples will be described with reference to verifying two signatures taken from the second left most subtree **208**. The example is highly simplified for the purposes of explanation. The simplified example uses an overall tree comprising an upper subtree **204** with an overall root node and two leaf nodes with no intermediate nodes, and two lower subtree nodes **206**, **208**; each subtree having a respective root node and two respective leaf nodes with no intermediate nodes. A consequence of such a simplified example is that the authentication paths are similarly simplified. As the heights of the subtrees increase, the authentication paths will become longer due to needing to relate to more nodes, including appropriate intermediate nodes.

Therefore, signing a message $m_{1,0}$ **262** with private key $sk_{1,0}$ **256** gives a signature and message combination of $Sig_{sk_{1,0}}(m_{1,0}),pk_1,Sig_{sk_1}(pk_1)$, and $m_{1,0}$ **262**, where:

- $Sig_{sk_{1,0}}(m_{1,0})$ is the OTS signature on the message $m_{1,0}$ using the private key $sk_{1,0}$ corresponding to the public key $pk_{1,0}$; and
- $Sig_{SK_1}(pk_1)$ is the OTS signature on the public key pk_1 **228** using private key SK_1 corresponding to the public key PK_1.

The tuple $Sig_{sk_{1,0}}(m_{1,0})$, $pk_1,Sig_{SK_1}(pk_1),A_{1,0}=\{pk_{1,1},PK_0\}$ is sent to the verifier, where

$A_{1,0}=\{pk_{1,1},PK_0\}$ is the associated authentication path. The message and $m_{1,0}$ **262** is also send to the verifier.

Assuming all hash values are calculated using the same one-way hash function H(key1,key2) and given the tuple $Sig_{sk_{1,0}}(m_{1,0}),pk_1,Sig_{SK_1}(pk_1),A_{1,0}=\{pk_{1,1},\ PK_0\}$ and the message $m_{1,0}$ **262**, verifying the public key $pk_{1,0}$ comprises performing the following:

1. Receiving $Sig_{sk_{1,0}}(m_{1,0}),pk_1,Sig_{SK_1}(pk_1),A_{1,0}=\{pk_{1,1},PK_0\}$ and the message $m_{1,0}$ **262**,
2. Calculating a candidate public key $pk'_{1,0}$ **250** using the signature $Sig_{sk_{1,0}}(m_{1,0})$ **256** and the message $m_{1,0}$ **262**;

3. Verifying the candidate public key $pk'_{1,0}$ **250** is in the tree with root node pk_1 using the respective authentication path $A_{1,0}=\{pk_{1,1},PK_0\}$ by:

3.1 calculating $H(pk'_{1,0}=pk'_{1,1})=pk'_1$, where pk'_1 is a candidate root node hash value of the root node of the subtree **208**;

3.2 If $pk'_1=pk_1$, continuing with:

3.2.1 calculating a further candidate public key PK'_1, using the received public key pk_1 and the respective signature $Sig_{SK_1}(pk_1)$ on pk_1 generated using SK_1

3.2.2 verifying the further candidate public key PK'_1 by:

3.2.2.1 calculating $PK'=H(PK_0,PK'_1)$,

3.2.2.2 If $PK'=PK$, concluding that:

the further candidate public key PK'_1 has been verified as valid,

the candidate public key $pk'_{1,0}$ **250** has been verified as valid, and

the candidate root node pk'_1 has been verified as valid.

Once the candidate root node $pk'_1=pk_1$ has been verified as valid, that verified hash value is stored as an entry **296** in the data structure **294**. The entry can comprise an indication of the verification status associated with the candidate root node pk'_1 such as the "Y" indicated, which represents "Yes—verified as value". However, examples can be realised in which the entry does not comprise an indication of the verification status associated with the candidate root node pk'_1 such as the "Y" indicated. The stored verified hash value is an example of a previously verified hash value associated with a previously received message. Although the examples described herein stored an indication of verification status, examples are not limited to such arrangements. Examples can be realised in which additional, or alternative, data is also stored. For instance, examples can be realised in which the additional, or alternative, data comprises an associated signature. In the present case, the additional, or alternative, data could comprise the signature $Sig_{SK_1}(pk_1)$ on.

The stored verified hash value pk'_1 can be used to verify future candidate public keys associated with the same tree or subtree as follows.

As indicated above, signing a message $m_{1,1}$ **264** with private key $sk_{1,1}$ **258** gives a signature and message combination of $Sig_{sk_{1,1}}(m_{1,1}),pk_1,Sig_{SK_1}(pk_1)$, where:

- $Sig_{sk_{1,1}}(m_{1,1})$ is the signature on the message $m_{1,1}$ using the private key $sk_{1,1}$ corresponding to the public key $pk_{1,1}$; and
- $Sig_{SK_1}(pk_1)$ is the signature on the public key pk_1 **228** using private key SK_1 corresponding to the public key PK_1.

The tuple $Sig_{sk_{1,1}}(m_{1,1}),pk_1,Sig_{SK_1}(pk_1),A_{1,1}=\{pk_{1,0},PK_0\}$ is sent to the verifier **104**, where $A_{1,1}=\{pk_{1,0},PK_0\}$ is the associated authentication path.

Assuming, again, that all hash values are calculated using the same one-way hash function H(key1, key2) and given the tuple $Sig_{sk_{1,1}}(m_{1,1}),pk_1,Sig_{SK_1}(pk_1),A_{1,1}=\{pk_{1,0},PK_0\}$, verifying the public key $pk_{1,1}$ comprises performing the following:

1. Receiving $Sig_{sk_{1,1}}(m_{1,1}),pk_1,Sig_{SK_1}(pk_1),A_{1,1}=\{pk_{1,0},PK_0\}$,
2. Calculating a candidate public key $pk'_{1,1}$ **252** using the signature $Sig_{sk_{1,1}}(m_{1,1})$ and the message $m_{1,1}$ **264**;
3. Verifying the candidate public key $pk'_{1,1}$ **252** is in the tree with root node pk_1 **228** using the respective authentication path $A_{1,1}=\{pk_{1,0},PK_0\}$ by:

3.1 calculating $H(pk_{1,0},pk'_{1,1})=pk'_1$, where pk'_1 is a candidate root node hash value of the root node of the subtree **208**;

3.2 accessing the data structure entry **296** corresponding to the calculated candidate root node hash value pk'_1 and determining that the candidate root node hash value pk'_1 has been previously verified as valid;

3.2.3 If pk'_1 has been previously verified as valid, concluding that the candidate public key $pk'_{1,1}$ **252** has been verified as valid.

It will be appreciated that the foregoing avoids, or otherwise saves, having to repeat all computations or processing associated with:

3.2.1 calculating a further candidate public key PK'_1, using the received public key pk_1 and the respective signature $Sig_{SK_1}(pk_1)$ on pk_1 generated using SK_1,

3.2.2 verifying the further candidate public key PK'_1 by:

3.2.2.1 calculating $PK'=H(PK_0, PK'_1)$,

3.2.2.2 If PK'=PK, concluding that:

the further candidate public key PK'_1 has been verified as valid,

the candidate public key $pk'_{1,0}$ **250** has been verified as valid, and

the candidate root node pk'_1 has been verified as valid.

Therefore, the bottom-up traversal of the tree structure **202** for verifying a public key, or any other values such as, for example, any hash values, can be terminated, insofar as concerns the current message $m_{1,1}$, when a previously verified as valid hash value has been encountered such as the candidate root node pk'_1.

When a candidate public key is verified, a message that was signed using the secret key corresponding to the verified candidate public key is deemed to be authentic.

As more messages are sent to the verifier **104**, the data structure **294** becomes increasingly populated with values that have been verified. For example, signing messages using respective secret keys that are associated with corresponding public keys that are part of the same, or a common, subtree reduces the overall verification process computational overhead to verifying a candidate public key, or other value, such as a hash value, up to the root node of that same, or common, subtree. Alternatively, or additionally, examples can be realised in which the verification process terminates at some other level or on some other condition such as, for example, a calculated hash value corresponding to a stored previously verified hash value. The calculated hash value or the stored previously verified hash value can be a hash value at any level of a subtree or tree.

Although the examples described herein refer to the data structures becoming increasingly populated, examples are not limited to such arrangements. Any and all examples can be realised in which the data within the data structures is managed or pruned, which can be useful in resource constrained environments. For instance, assuming that pk_0 is stored along with the signature $Sig_{SK_0}(pk_0)$ on pk_0, that information will be used to efficiently verify signatures on messages up to 248. Then message $m_{1,0}$ **262** will use pk_1 instead of pk_0. The verifier **104** can then replace pk_0, $Sig_{SK_0}(pk_0)$ with pk_1, $Sig_{SK_1}(pk_1)$, since pk_0 will not be used again.

Although the examples herein have been described with reference to storing the verified hash values, such as the verified root hash values, in the data structures, examples are not limited to such arrangements. Examples can be realised in which respective sets of further data (not shown) are also stored within the data structures. For example, examples can be realised in which the data structures can store at least one or more than one, taken jointly and severally in any and all permutations, of: {a verified public key and a confirmation of verification status such as (pk_0, yes), a verified public key and an associated signature on that verified public key such as (pk_0,$Sig_{SK_0}(pk_0)$)}. Examples can be realised in which a data structure has a one-to-one correspondence with an overall root node to accommodate situations in which there are multiple different signers with multiple different public keys, that is, there will be one data structure per overall root node. Therefore, in such circumstances reaching a conclusion that a calculated hash value corresponding to stored previously calculated hash value will be conditional on multiple criteria being met; the criteria being related to the additional data contained within the one or more than one sets of further data.

Referring to FIG. **3**, there is shown a view **300** of a single Merkle tree **302**. The Merkle tree **302** can be used to verify or authenticate a plurality of messages **304** to **318** that have been signed using respective private keys **320** to **334**. The private keys **320** to **334** form part of a number of private-public key pairs. Each private-public key pair also comprises a respective public key **336** to **350**. Additionally, or alternatively, the Merkle tree can be used to verify a candidate public key in response to receiving a message and a corresponding signature on the message created using a respective private key.

Assuming all hash values are calculated using the same one-way hash function H(key1, key2) and given a previously received root hash value PK **351** and a received tuple $Sig_{SK_0}(m_0)$, m_0, $A_0=\{PK_1,P_1,P_5\}$, where:

m_0 is a message,

$Sig_{SK_0}(m_0)$ is the OTS signature on the message m_0 **304** signed using a private key SK_0 **320**,

$A_0=\{PK_1,P_1,P_5\}$ is the authentication path comprising hash values PK_1,P_1,P_5,

verifying a candidate public key PK'_0 comprises performing the following:

1. Receiving $Sig_{SK_0}(m_0)$, m_0,$A_0=\{PK_1,P_1,P_5\}$,
2. Calculating a candidate public key PK'_0 **336** using the signature $Sig_{SK_0}(m_0)$ and the message m_0 **304**;
3. Calculating hash value $P'_0=H(PK'_0, PK_1)$ **352**, **352'**,
4. Calculating hash value $P'_4=H(P'_0, P_1)$ **354**, **354'**,
5. Calculating hash value $PK'=H(P'_4, P_5)$ **356**, **356'**
6. Verifying the candidate public key PK'_0 **336** as valid if PK'=PK.

Once the candidate public key PK'_0 **336** has been verified, a data structure **358** can be populated with a set of hash values that are known to be verified or authentic. The set of hash values can comprise one or more than one hash value selected from the set $\{PK'_0, PK_1, P'_0, P_1, P'_4, P_5\}$. Examples can be realised in which each verified hash value of the set of hash values is stored in the data structure **358**. However, examples are not limited to such an arrangement. Examples can be realised in which a subset of verified hash values is stored in the data structure **358**. For example, a constrained resource device might not have memory to store a large data structure comprising all verified hash values. In such a constrained resource device a selected subset of hash values of the verified hash values can be stored. Such a subset might contain a single verified hash value.

Populating the data structure **358** with all verified hash values following verifying candidate public key PK'_0 **336** gives the set $\{P'_0, P_1, P'_4, P_5\}$ of verified hash values **360** excluding leaf nodes. It can be appreciated that only two hash values P_2 **368** and P_3 **370** are missing from the data structure **358** of verified data. The data structure **358** will be populated with a verified hash value P_2 **368** when the verifier **104** receives the message m_4 **312** and the associated signature $Sig_{SK_1}(m_4)$ from which a candidate public key PK_4 **344** can be calculated for verification and will also be populated with a verified hash value P_3 **370** since that hash value will have been provided as part of the authentication path for message m_4 **312**.

The data in the data structure **358** can be used to reduce the computational resources used to verify a subsequent candidate public key.

Assuming, again, all hash values are calculated using the same one-way hash function H(key1, key2) and given the previously received root hash value PK **351** and a received tuple $Sig_{SK_1}(m_1)$, m_1, $A_1=\{PK_0, P_1, P_5\}$, where:

m_1 is a message **306**,

$Sig_{SK_1}(m_1)$ is the signature of the message m_1 **306** signed using a private key SK_1 **322**,

$A_1=\{PK_0, P_1, P_5\}$ is the authentication path comprising hash values PK_0, P_1, P_5,

verifying a candidate public key PK'_1 **338** comprises performing the following:

1. Receiving $Sig_{SK_1}(m_1)$,m_1, $A_1=\{PK_0, P_1, P_5\}$,
2. Calculating a candidate public key PK'_1 **338** using the signature $Sig_{SK_1}(m_1)$ and the message m_1 **306**;
3. Calculating hash value $P'_0=H(PK_0,PK'_1)$ **352**, **352'**,
4 Accessing the data structure **358** to determine whether or not there is an entry **360** corresponding to the calculated hash value P'_0 **252** and determining that the calculated hash value P'_0 **352** has been previously verified as valid;
5. If P'_0 **352** has been previously verified as valid, concluding that the candidate public key PK'_1 **338** has been verified as valid.

It will be appreciated that the foregoing avoids or otherwise saves having to repeat all computations and processing associated with:

Calculating hash value $P'_4=H(P'_0, P_1)$ **354**, **354'**,

Calculating hash value $PK'=H(P'_4, P_5)$ **356**, **356'**, and

Verifying the candidate public key PK'_0 **336** as valid if PK'=PK.

Therefore, the bottom-up traversal of the tree structure **302** can be terminated, insofar as concerns the current message m_1 when a previously verified as valid hash value has been encountered.

Referring to FIG. **4**, there is shown a pair of flow charts **402** and **404** for verifying a candidate public key as valid according to examples.

Referring to the left-hand flowchart **402**, at **406**, a message and corresponding signature are received. A candidate public key is derived from the received message and corresponding signature at **408**. At **410**, a hash value is calculated that is related to the candidate public key. A determination is made, at **412**, of whether or not the calculated hash value is, or corresponds to, a previously verified hash value. The candidate public key is verified as valid based on the previously verified hash value at **414**.

Referring to the right-hand flowchart **404**, at **416**, a message and corresponding signature are received and a candidate public key is derived from the received message and corresponding signature. At **418**, traversal of the tree is commenced in a bottom-up manner. At **420**, a next hash value is calculated that is related to the candidate public key. A determination is made, at **422**, of whether or not the calculated hash value is, or corresponds to, a previously verified hash value. If the calculated hash value is not, or does not correspond to, a previously verified hash value, processing returns to **420**, where the next hash value is calculated. However, if the calculated hash value is, or corresponds to, a previously calculated hash value, the candidate public key is verified as value at **424** and the bottom-up traversal of the tree is terminated insofar as concerns the currently received message.

The functionality of the system **100**, the signer **102** and the verifier **104** can be realised in the form of machine instructions that can be processed by a machine comprising or having access to the instructions. The machine can comprise a computer, processor, processor core, DSP, a special purpose processor implementing the instructions such as, for example, an FPGA or an ASIC, circuitry or other logic, compiler, translator, interpreter or any other instruction processor. Processing the instructions can comprise interpreting, executing, converting, translating or otherwise giving effect to the instructions. The instructions can be stored on a machine readable medium, which is an example of machine-readable storage. The machine-readable medium can store the instructions in a non-volatile, non-transient or non-transitory, manner or in a volatile, transient, manner, where the term 'non-transitory' does not encompass transitory propagating signals. The instructions can be arranged to give effect to any and all operations described herein taken jointly and severally in any and all permutations. The instructions can be arranged to give effect to any and all of the operations, devices, HSMs, dealers, systems, authenticators, flowcharts, protocols or methods described herein taken jointly and severally in any and all permutations. In particular, the machine instructions can give effect to, or otherwise implement, the operations of the flowcharts depicted in, or described with reference to, FIGS. **4**, **5** and **6**, taken jointly and severally in any and all permutations.

Therefore, FIG. **5** shows a view **500** of machine instructions **502** stored using machine readable storage **504** for implementing the examples described herein. The machine instructions **502** can be processed by, for example, a processor **506** or other processing entity, such as, for example, an interpreter, as indicated above.

The machine instructions **502** comprise at least one or more than one of:

Instructions **508** to receive a message,

Instructions **510** to receive a signature associated with the message,

Instructions **512** to generate a candidate public key from the received message and received signature,

Instructions **514** to calculate a hash value given respective input parameters,

Instructions **516** to determine from a data structure **518** stored in memory **520** whether or not a calculated hash value has been previously verified as valid, and

Instructions **522** to verify as valid a calculated hash value in response to determining that the calculated hash value has been previously verified as valid;

Instructions **524** to store a hash value that has been verified as valid;

the foregoing instructions **508** to **524** being taken jointly and severally in any and all permutations.

The above examples contrast with existing digital hash-based signature schemes in which all hash values leading from a leaf node to an overall root node are calculated to establish that a received signature is valid and, therefore, that a corresponding message is authentic. Terminating the bottom-up traversal of the tree structure when a previously verified valid hash value is encountered saves a significant number of calculations used to verify a received signature as valid and, therefore, to authenticate a corresponding message as authentic. The computational saving increases as the number of levels of a tree increased and as the number of sub-trees increases.

It will be appreciated that a the Merkle tree comprises: 2^h one-time key pairs (sk_j,pk_j), where $0 \leq j < 2^h$, and the previously stored previously verified hash value associated with the previously received message comprises: one or more than one of a plurality of hash values $q_1, \ldots, q_{2^{h+1}-1}$ where $q_i = H(q_{2i} \| q_{2i+1})$ for $1 \leq i < 2^h$, $q_{2^h+1} = H(pk^{(j)})$ for $0 \leq j < 2^h$ and the overall public key is $Y = q_1$.

Although the examples herein have been described using a one-way hash function H(key1,key2), examples are not limited to such a one-way hash function. Examples can be realised in which other one-way hash functions can be used. For examples, any and all examples can use one-way hash functions that take more than two parameters. Examples can be realised in which the one-way hash functions take a plurality of parameters. For instance, examples can be realised in which the one-way hash functions also have a third parameter. The third parameter can be a seed such as, for example, a randomness seed that would give a one-way hash function of H(key1,key2,randomness).

Therefore, the examples described herein facilitate authentication. Authentication is the assurance that a given entity was the original source of received data. The received data can comprise at least one, or both, of: a message and a signature derived from the message. The authentication uses a digital signature scheme. A digital signature scheme can provide authentication and comprises three algorithms, which are key generation, signature generation and verification, that is (KeyGen, Sign, Verify). The verification algorithm is run by a verifier such as any of the verifiers described herein, and takes as input any public parameters and the tuple (public_key, message, signature) and outputs either 'valid' or 'invalid'. If the verification algorithm outputs 'valid', then the verifier has assurance that a given entity was the original source of the received data (message and signature), that is, to authenticate a message, the verifier must verify the signature and receive a 'valid' output; a valid signature provides authentication to the verifier.

One or more of the examples provided herein support methods of verifying a message as authentic; the message having an associated composite signature comprising a number of signatures associated with Merkle subtrees of an overall Merkel tree; the methods comprising verifying, in turn, a subset signatures of the number of signature until a hash value associated with a signature is encountered that has been previously verified as valid, and determining that the composite signature is valid in response to encountering the hash value associated with the signature that has been previously verified as valid. Examples can be realised in which the subset of signatures comprises fewer signatures that the number of signatures of the composite signature. Examples can be realised in which the hash value previously verified as valid is associated a root node of at least one Merkle subtree of the Merkle subtrees.

Examples can be realised according to the following clauses:

Clause 1: A method of verifying as valid a received signature, associated with a received message, generated using a Merkle Signature Scheme comprising a Merkle Tree, the Merkel Tree comprising a root node, a number of leaf nodes and a number of intermediate nodes disposed between the root node and the leaf nodes; the method comprising: calculating a hash value in response to receiving the message; determining that the calculated hash value corresponds to a stored previously verified hash value calculated in response to a previously received message, and verifying the received signature as valid based on the stored previously verified hash value.

Clause 2: The method of clause 1, in which calculating a hash value in response to receiving the message comprises: calculating a hash value related to the root node.

Clause 3: The method of any preceding clause, in which calculating a hash value in response to receiving the message comprises: calculating a hash value associated with an authentication path related to the received message.

Clause 4: The method of any preceding clause, in which the Merkle Tree a multi-tree Merkle Tree comprising a number of subtrees, each subtree comprising a respective subtree root node, a respective number of leaf nodes and a number of intermediate nodes disposed between the respective subtree root node and respective leaf node, and in which the root node is associated with one of the sub-trees.

Clause 5: The method of clause 4, in which calculating a hash value in response to receiving the message comprises: calculating the hash value associated with a respective root node of a subtree of the number of subtrees.

Clause 6: The method of any preceding clause, in which: the Merkle tree comprises: 2^h one-time key pairs (sk_j, pk_j), where $0 \leq j < 2^h$, and the previously stored previously verified hash value associated with the previously received message comprises: one or more than one of a plurality of hash values $q_1, \ldots, q_{2^{h+1}-1}$ where $q_i = H(q_{2i} \| q_{2i+1})$ for $1 \leq i < 2^h$, $q_{2^h+j} = H(pk^{(j)})$ for $0 \leq j < 2^h$ and the overall public key is $Y = q_1$.

Clause 7: The method of any preceding clause, comprising calculating, verifying and storing the verified hash value calculated in response to the previously stored message.

Clause 8: The method of any preceding clause, comprising: terminating traversing of the Merkle Tree at a node, such as, for example, a root node, of a subtree corresponding to the calculated hash value that corresponds to the stored previously verified hash value in response to said verifying the received signature as valid based on the stored previously verified hash value associated with the previously received message.

Clause 9: The method of any preceding clause, comprising: traversing the Merkle Tree from a leaf node associated with the received message having a respective authentication path comprising at least respective intermediate nodes; said traversing comprising said: calculating a hash value in response to receiving the message; determining that the calculated hash value corresponds to a stored previously verified hash value calculated in response to a previously received message, and verifying the received signature as valid based on the stored previously verified hash value calculated in response to the previously received message, and terminating said traversing of the Merkle Tree in response to said verifying the received signature as valid based on the stored previously verified hash value calculated in response to the previously received message; said terminating being at a root node of a subtree corresponding to the calculated hash value corresponding to the stored previously verified hash value.

Clause 10: The method of any preceding clause, comprising: traversing the Merkle Tree from a leaf node associated with the received message having a respective authentication path comprising at least respective intermediate nodes; said traversing comprising said: calculating a hash value in response to receiving the respective message; determining that the calculated hash value corresponds to a stored previously verified hash value calculated in response to a previously received message, and verifying the received signature as valid based on the stored previously verified hash value, and terminating said traversing of the Merkle Tree in response to said verifying the received signature as valid based on the stored previously verified hash value associated with the previously received message; said terminating being at an intermediate node corresponding to the calculated hash value corresponding to the stored previously verified hash value.

Clause 11: A method of authenticating a block of data of a plurality of blocks of data; the method comprising: receiving the block of data and a respective signature; verifying the received signature as valid based on a previously verified hash value calculated in response to a previously received message of any preceding clause; designating the received block of data as authentic in response to said verifying the received signature as valid.

Clause 12: The method of clause 11, in which the plurality of blocks of data represent software.

Clause 13: A device for verifying code as authentic, the code having an associated received signature generated using a hash based signature scheme comprising a tree structure, the tree structure comprising a root node, a number of leaf nodes and a number of intermediate nodes disposed between the root node and the leaf nodes; the device comprising logic to comprising: receive a portion of data associated with the code and the signature; the portion of data associated with the code being one of a number of portions of data associated with the whole of the code; calculate a hash value in response to receiving the portion of data associated with the code; determine that the calculated hash value corresponds to a stored previously verified hash value calculated in response to receiving a previously received portion of data associated with the code, and verify the received portion of data as valid based on the previously verified hash value calculated in response to receiving the previously received portion of data associated with the code.

Clause 14: The device of clause 13, comprising logic to verify the whole of the code as authentic in response to verifying as authentic each portion of data of the number of portions of data.

Clause 15: A method of verifying as valid a current composite signature associated with a currently received message; the current composite signature comprising a number of signatures; the method comprising: verifying as valid a previously received composite signature, comprising a number of previously received signatures, associated with a previously received message including verifying as valid the number of previously received signatures; verifying as valid the current composite signature by verifying as valid a signature of the number of signatures of the current composite signature; and establishing that a further signature of the number of signatures of the current composite signature is common to a previously received signature verified as valid of the number of previously received signatures.

Clause 16: A method of verifying as valid a signature, associated with a message, generated using a Hash Based Signature Scheme having an associated Multi-Tree structure comprising an overall root node, having a respective public key, and two or more levels of sub-trees; the method comprising: verifying as valid a OTS associated with the respective message; establishing that the OTS is derived from a private key of a sub-tree having a previously verified root node hash value; determining, in response to said establishing, that the signature associated with the respective message is valid.

Clause 17: Machine-instructions arranged, when processed, for implementing any method of any of clauses 1 to 12, and clauses 15 to 16.

Clause 18: Machine-readable storage storing machine-instructions of clause 17.

The invention claimed is:

1. A non-transitory machine-readable storage storing machine-instructions arranged, when processed by a processor, to

verify as valid a signature generated using a Merkle Signature Scheme comprising a Merkle Tree, the Merkle Tree comprising:

a root node;

a number of leaf nodes; and

a plurality of intermediate nodes disposed between the root node and the leaf nodes;

wherein verifying the signature as valid includes:

receiving the signature and a message associated with the signature;

deriving a candidate public key from the signature and the message;

calculating a hash value in response to receiving the message;

calculating a first hash value using the candidate public key;

determining that the first hash value corresponds to a stored previously verified second hash value, wherein the stored previously verified second hash value was calculated in response to a previously received message; and

verifying the candidate public key as valid based on the stored previously verified second hash value, wherein verifying the candidate public key verifies the signature.

2. The non-transitory machine-readable storage of claim **1**, comprising further instructions that, when executed by the processor, cause the processor to calculate a hash value related to the root node in response to receiving the message.

3. The non-transitory machine-readable storage of claim **1**, comprising further instructions that, when executed by the processor, cause the processor to, in response to receiving the message, calculate a hash value associated with an authentication path related to the message.

4. The non-transitory machine-readable storage of claim **1**, wherein the Merkle Tree is a multi-tree Merkle Tree comprising a number of subtrees, and wherein each subtree comprises an independent subtree root node, and wherein the number of leaf nodes and a number of intermediate nodes are disposed between the subtree root node and leaf nodes, and further wherein the root node is associated with one of the subtrees.

5. The non-transitory machine-readable storage of claim **4**, comprising further instructions that, when executed by the processor, cause the processor to, in response to receiving the message, calculate the hash value associated with a respective root node of a subtree of the number of subtrees.

6. The non-transitory machine-readable storage of claim **1**, wherein the Merkle tree comprises:

2^h one-time key pairs (sk_j, pk_j), where $0 \leq j < 2^h$, and

wherein the previously stored previously verified second hash value associated with the previously received message comprises:

one or more than one of a plurality of hash values $q_1, \ldots, q_{2^{h+1}-1}$ where $q_i = H(q_{2i} \| q_{2i+1})$ for $1 \leq i < 2^h$, $q_{2^h+j} = H(pk^{(j)})$ for $0 \leq j < 2^h$ and an overall public key is $Y = q_1$.

7. The non-transitory machine-readable storage of claim **1**, comprising further instructions that, when executed by the processor, cause the processor to calculate, verify and store the second hash value calculated in response to the previously received message.

8. The non-transitory machine-readable storage of claim **1**, comprising further instructions that, when executed by the processor, cause the processor to terminate traversing of the Merkle Tree at a node of a subtree corresponding to the first hash value that corresponds to the stored previously verified second hash value in response to verifying the received signature as valid based on the stored previously verified second hash value associated with the previously received message.

9. The non-transitory machine-readable storage of claim **1**, comprising further instructions that, when executed by the processor, cause the processor to:

traverse the Merkle Tree from a leaf node associated with the message having a respective authentication path comprising at least respective intermediate nodes, wherein traversing the Merkle Tree includes:

calculating a hash value in response to receiving the message;

determining that the first hash value corresponds to a stored previously verified second hash value calculated in response to the previously received message; and

verify the received signature as valid based on the stored previously verified second hash value calculated in response to the previously received message and

terminate the traversing of the Merkle Tree in response to the verification of the received signature as valid based on the stored previously verified second hash value calculated in response to the previously received message, wherein terminating at a root node of a subtree corresponds to the first hash value corresponding to the stored previously verified second hash value.

10. The non-transitory machine-readable storage of claim **1**, comprising further instructions that, when executed by the processor, cause the processor to:

traverse the Merkle Tree from a leaf node associated with the message having a respective authentication path comprising at least respective intermediate nodes, wherein traversing the Merkle Tree includes:

calculating a hash value in response to receiving the message;

determining that the first hash value corresponds to a stored previously verified second hash value calculated in response to the previously received message; and

verifying the received signature as valid based on the stored previously verified second hash value; and

terminating traversing of the Merkle Tree in response to verifying the received signature as valid based on the

stored previously verified second hash value associated with the previously received message, wherein terminating being at an intermediate node corresponding to the first hash value corresponding to the stored previously verified second hash value.

11. A computing device comprising:

a non-transitory memory storing instructions for verifying code as authentic, wherein the code comprises an associated received signature generated using a hash based signature scheme comprising a tree structure, and wherein the tree structure comprises:

a root node;

a number of leaf nodes; and

a number of intermediate nodes disposed between the root node and the leaf nodes; and

a processor in communication with the non-transitory memory, wherein the processor is to:

receive a portion of data associated with the code and the signature, wherein the portion of data associated with the code is one of a number of portions of data associated with the code;

derive a candidate public key from the signature and the portion of data associated with the code;

calculate a first hash value in response to receiving the portion of data associated with the code;

determine that the first hash value corresponds to a stored previously verified second hash value calculated in response to receiving a previously received portion of data associated with the code; and

verify the candidate public key as valid based on the previously verified second hash value calculated in response to receiving the previously received portion of data associated with the code, wherein verifying the candidate public key verifies the signature.

12. The computing device of claim **11**, wherein the processor is further to verify the code as authentic in response to verifying as authentic each portion of data of the number of portions of data.

13. A non-transitory computer-readable medium comprising instructions that, when executed by a processor, cause the processor to:

verify as valid a current composite signature associated with a currently received message, wherein the current composite signature comprises a number of signatures;

verify as valid a previously received composite signature, comprising a number of previously received signatures, associated with a previously received message including verifying as valid the number of previously received signatures;

verify as valid a signature of the number of signatures of the current composite signature; and

establish that a further signature of the number of signatures of the current composite signature is common to a previously received signature that was previously verified as valid, the previously received signature being one of the number of previously received signatures.

14. The non-transitory computer-readable medium of claim **13**, comprising further instructions that, when executed by the processor, cause the processor to:

verify as valid a previously received composite signature, comprising a number of previously received signatures, associated with the previously received message including instructions to verify as valid the number of previously received signatures; and verify as valid a previously received signature associated with a root node of a subtree of a Merkle tree used to verify as valid the current composite signature.

15. The non-transitory computer-readable medium of claim **13**, comprising further instructions that, when executed by the processor, cause the processor to store in a data structure a previously received signature that was verified as valid.

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