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Stateless Hash-Based Signatures in Merkle Tree Ladder Mode (SLH-DSA-MTL) for DNSSEC

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Abstract

This document describes how to apply the Stateless Hash-Based Digital Signature Algorithm in Merkle Tree Ladder mode to the DNS Security Extensions. This combination is referred to as the SLH-DSA-MTL Signature scheme. This document describes how to specify SLH-DSA-MTL keys and signatures in DNSSEC. It uses both the SHA2 and SHAKE family of hash functions. This document also provides guidance for use of EDNS(0) in signature retrieval.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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1. Introduction

The Domain Name System Security Extensions (DNSSEC), which are broadly defined in [RFC4033], [RFC4034] and [RFC4035], use cryptographic keys and digital signatures to provide data origin authentication and data integrity in the DNS. This document describes the application of Merkle Tree Ladder (MTL) Mode to the Stateless Hash-Based Digital Signature Algorithm (SLH-DSA) as the SLH-DSA-MTL signature scheme for DNSSEC. SLH-DSA is described in the FIPS 205 standard [FIPS205] and MTL mode is described in [I-D.harvey-cfrg-mtl-mode]. As described herein, a DNSKEY resource record (RR) for an SLH-DSA-MTL key contains a SLH-DSA key. The SLH-DSA key is used for verifying signatures on Merkle tree ladders (MTLs). An RRSIG resource record for an SLH-DSA-MTL Signature contains a Merkle proof (authentication path) that is verifiable using a MTL, and optionally also contains the signed MTL.

The anticipation of quantum computers that can break the current signature algorithms led to NIST selecting post-quantum cryptographic (PQC) algorithms for standardization and developing specifications for the algorithms as NIST standards. These new algorithms are expected to replace classical digital signature algorithms (e.g., RSA and ECDSA) in IETF standards and to be widely implemented and deployed after that. NIST’s proposed PQC algorithms have significantly larger signature sizes than RSA and ECDSA. The larger sizes may have a significant operational impact on DNSSEC. For example, the size of signed NSEC and NSEC3 responses may exceed UDP MTUs with this degrading the use of UDP as the prevalent DNSSEC transport. Larger signature sizes could also substantially increase memory requirements for in-memory zone databases used by authoritative name servers and for in-memory caches used by resolvers.

As described in [I-D.harvey-cfrg-mtl-mode], MTL mode is designed to reduce the size impact of PQC signature algorithms. For DNSSEC, the size impact reduction is achieved when signatures provided in RRSIG RRs are primarily comprised of "condensed signatures" (Merkle proofs / authentication paths) and are only occasionally comprised of "full signatures" that contain both a condensed signature and a signed MTL, where the signed ladder includes a signature using the underlying PQC signature algorithm. MTL mode reduces the memory requirements for PQC signatures as the signature data in the zone database or cache is primarily comprised of Merkle proofs and only occasionally of signed MTLs [CTRSAMTL].

SLH-DSA is a stateless hash-based PQC signature scheme selected by NIST for standardization [NISTSELECTIONS] in July 2022 and formally published as a standard in August 2024 [FIPS205]. This document

specifies SLH-DSA for the initial application of MTL mode to DNSSEC based on three considerations: (1) SLH-DSA is also based on Merkle trees, and thus already has internal functions for computing leaf nodes and internal nodes; and (2) SLH-DSA has relatively large signature sizes and computational costs, and therefore can benefit significantly from the reductions offered by MTL mode; and (3) hash-based techniques are well understood and offer a conservative choice for long-term security relative to newer NIST selected signature schemes based on lattice-based cryptography. SLH-DSA is based on SPHINCS+ [SPHINCSPLUS], one of the submissions to NIST's PQC evaluation project [I-D.harvey-cfrg-mtl-mode] describes the combination of MTL mode with SLH-DSA.

This initial version of the draft focuses on the code-points applicable to DNSKEY and RRSIG formulation and a proposed DNSSEC protocol change to support retrieval of MTL mode condensed signatures and MTL mode full signatures as described in Section 3, Section 9.4, and Section 9.5 of [I-D.harvey-cfrg-mtl-mode]. Later versions may describe DNSSEC protocol and/or operational changes related to zone signing, zone composition, zone updates, zone transfer, name server processing, resolver signature processing, and resolver caching.

2. Conventions Used in This Document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

Double pipe characters, "||" are used in this document to indicate concatenation of the elements preceding and following the double pipe characters.

All numeric DNSKEY elements and RRSIG elements specified in this document are unsigned integers in network byte order (big endian order).

3. DNSKEY Resource Records

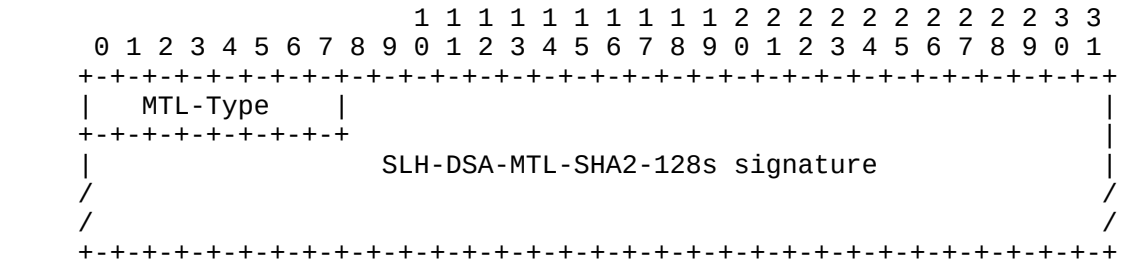
An SLHDSAMTLSHA2128S key consists of a 32-octet value, which is encoded into the Public Key field of a DNSKEY resource record as a simple bit string. SLHDSAMTLSHA2128S keys are generated as SLH-DSA keys using the SLH-DSA-SHA2-128s parameter set, as defined in 10.1 and 11 of [FIPS205].

An SLHDSAMTLSHAKE128S key consists of a 32-octet value, which is encoded into the Public Key field of a DNSKEY resource record as a simple bit string. SLHDSAMTLSHAKE128S keys are generated as SLH-DSA keys using the SLH-DSA-SHAKE-128s parameter set, as defined in 10.1 and 11 of [FIPS205].

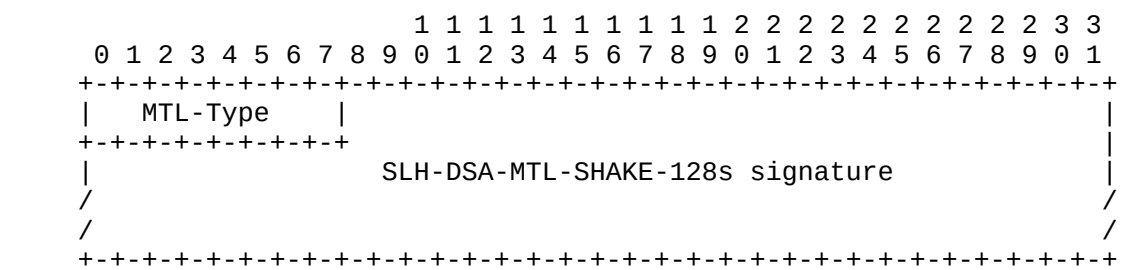
4. RRSIG Resource Records

MTL mode signatures are either full or condensed as described in [I-D.harvey-cfrg-mtl-mode]. SLHDSAMTLSHA2128S and SLHDSAMTLSHAKE128S signatures utilize a one-octet prefixed MTL-Type field to indicate whether the signature is condensed (0) or full (1).

An SLHDSAMTLSHA2128S signature consists of a variable-length value, which is encoded into the Signature field of an RRSIG resource record as a simple bit string as the concatenation of the MTL-Type and a SLH-DSA-MTL-SHA2-128s signature as described in [I-D.harvey-cfrg-mtl-mode]:



An SLHDSAMTLSHAKE128S signature consists of a variable-length value, which is encoded into the Signature field of an RRSIG resource record as a simple bit string as the concatenation of the MTL-Type and a SLH-DSA-MTL-SHAKE-128s signature as described in [I-D.harvey-cfrg-mtl-mode]:



The signature and verification algorithms for both SLH-DSA-MTL-SHA2-128s and SLH-DSA-MTL-SHAKE-128s are described in 9.1 and 9.2 of [I-D.harvey-cfrg-mtl-mode]. The signature and verification

algorithms for the underlying signature algorithms used for signing ladders in SLH-DSA-MTL-SHA2-128s and SLH-DSA-MTL-SHAKE-128s full signatures, SLH-DSA-SHA2-128s and SLH-DSA-SHAKE-128s respectively, are described in 10.2 and 10.3 of [FIPS205].

5. Algorithm Numbers for DS, DNSKEY, and RRSIG Resource Records

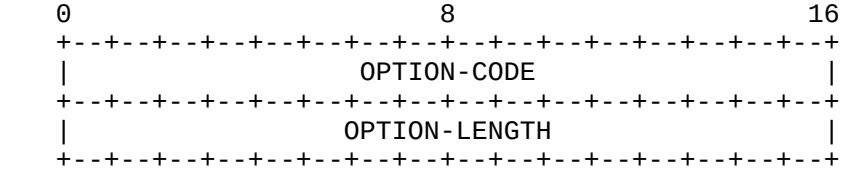
The algorithm number associated with the use of SLHDSAMTLSHA2128S in DS, DNSKEY, and RRSIG resource records is TBD. The algorithm number associated with the use of SLHDSAMTLSHAKE128S in DS, DNSKEY, and RRSIG resource records is TBD. This registration is fully defined in the IANA Considerations section.

6. The mtl-mode-full EDNS(0) Option

MTL mode signatures are either full or condensed. A MTL mode-aware client MAY request that signatures be returned in the full format by providing the mtl-mode-full EDNS(0) option in the OPT meta-RR of its query [RFC6891].

6.1. Option Format

The mtl-mode-full option is encoded as follows:



Where:

OPTION-CODE The EDNS0 option code assigned to mtl-mode-full, TBD.
OPTION-LENGTH Always zero.

6.2. Use By Responders

When a query includes the mtl-mode-full option, the response requirement depends on the number of RRSIG records in the response that were produced in MTL mode:

* If exactly one RRSIG record in the response was produced in MTL mode, then that RRSIG record MUST be returned in the full signature format.

* If more than one RRSIG record in the response was produced in MTL mode, then enough of these RRSIG records MUST be returned in the full signature format to ensure that every other RRSIG in the response that was produced in MTL mode can be verified.

When the mtl-mode-full option is not included, every signature in the response that was produced in MTL mode MUST be returned in the condensed signature format.

As described in 9.2 of [I-D.harvey-cfrg-mtl-mode], when a verifier receives a condensed signature, the verifier determines whether any of the MTLs it has previously verified includes a rung that is compatible with the authentication path in the condensed signature. If not, then the verifier requests a new signed ladder. Accordingly, a resolver SHOULD first query a name server without the mtl-mode-full option, and then, if needed, re-issue the query with the mtl-mode-full option. Since responses to queries with the mtl-mode-full option are expected to be large, it is RECOMMENDED that queries with the mtl-mode-full option be issued over transports (e.g., TCP, TLS, QUIC) that support large responses without truncation and/or fragmentation.

7. Implementation Considerations

Signing RRSets in batches rather than as individual messages can leverage MTL mode to reduce the number of public/private key signing operations performed with the underlying signature algorithm. This results in reducing the average computational overhead per message signed. This practice can also reduce the load on a hardware security module. Batches also benefit the verifier by reducing the number of full signatures required for validation because multiple RRSIGs can be verified by the ladder covering the batch. The appropriate batch size will depend on the properties of the zone and the requirements of the zone operator. Batch size needs to be considered carefully to ensure that new signatures are available in a timely manner while still gaining the benefits of batch signing [MTL-ENDURANCE].

8. Examples

Examples with detailed processing descriptions are found in Appendix A

9. IANA Considerations

This document updates the IANA registry for DNSSEC "Domain Name System Security (DNSSEC) Algorithm Numbers" located at https://www.iana.org/assignments/dns-sec-alg-numbers/dns-sec-alg-numbers.xhtml (https://www.iana.org/assignments/dns-sec-alg-numbers/dns-sec-alg-numbers.xhtml). The following entries are requested to be added to the registry subject to the Number update:

SLH-DSA-MTL-SHA2-128s

Number	TBD
Description	SLH-DSA-MTL-SHA2-128s
Mnemonic	SLHDSAMTLSHA2128S
Zone Signing	Y
Trans. Sec.	*
Reference	This specification

SLH-DSA-MTL-SHAKE-128s

Number	TBD
Description	SLH-DSA-MTL-SHAKE-128s
Mnemonic	SLHDSAMTLSHAKE128S
Zone Signing	Y
Trans. Sec.	*
Reference	This specification

* There has been no determination of standardization of the use of these algorithms with Transaction Security.

10. Implementation Status

NOTE: Please remove this section and the reference to RFC 7942 prior to publication as an RFC.

This section records the status of known implementations of the protocol defined by this specification at the time of posting of this Internet-Draft, and is based on a proposal described in RFC 7942. The description of implementations in this section is intended to assist the IETF in its decision processes in progressing drafts to RFCs. Please note that the listing of any individual implementation here does not imply endorsement by the IETF. Furthermore, no effort has been spent to verify the information presented here that was supplied by IETF contributors. This is not intended as, and must not be construed to be, a catalog of available implementations or their features. Readers are advised to note that other implementations may exist.

According to RFC 7942, "this will allow reviewers and working groups to assign due consideration to documents that have the benefit of running code, which may serve as evidence of valuable experimentation and feedback that have made the implemented protocols more mature. It is up to the individual working groups to use this information as they see fit".

For testing purposes, SLH-DSA-MTL-DNSSEC has been implemented in the following DNS open-source applications:

* LDNS for key generation, zone signing, and zone verification with MTL mode: https://github.com/Verisign/mtl-mode-ldns (https://github.com/Verisign/mtl-mode-ldns)
* NSD authoritative name server with MTL mode: https://github.com/NLnetLabs/nsd/pull/397 (https://github.com/NLnetLabs/nsd/pull/397)
* Unbound recursive resolver with MTL mode: https://github.com/Verisign/mtl-mode-unbound (https://github.com/Verisign/mtl-mode-unbound)

These implementations depend on the reference implementation of MTL mode which is available in C. The MTL library can be found at https://github.com/Verisign/MTL (https://github.com/Verisign/MTL).

11. Security Considerations

The security considerations of [FIPS205] and [I-D.harvey-cfrg-mtl-mode] are inherited in the usage of SLH-DSA-MTL in DNSSEC.

SLH-DSA-MTL-SHA2-128s and SLH-DSA-MTL-SHAKE-128s are intended to operate at around the 128-bit security level against classical attacks and the 64-bit level against quantum attacks, consistent with NIST’s security level I.

A private key used for a DNSSEC zone MUST NOT be used for any other purpose than for that zone. Otherwise, cross-protocol or cross-application attacks are possible.

12. Acknowledgements

The authors would like to acknowledge the following individuals for their contributions to the development of this document: Scott Hollenbeck, Swapneel Sheth. This I-D has drawn from helpful examples of document structure and specification text from various DNSSEC algorithm RFCs. The authors express their gratitude to the authors of those RFCs for their contributions.

13. References

13.1. Normative References

[FIPS205] National Institute of Standards and Technology (NIST), "Stateless Hash-Based Digital Signature Standard", FIPS PUB 205, DOI 10.6028/NIST.FIPS.205, 13 August 2024, <https://doi.org/10.6028/NIST.FIPS.205>.

[I-D.harvey-cfrg-mtl-mode] Harvey, J., Kaliski, B., Fregly, A., and S. Sheth, "Merkle Tree Ladder (MTL) Mode Signatures", Work in Progress, Internet-Draft, draft-harvey-cfrg-mtl-mode-07, 9 September 2025, <https://datatracker.ietf.org/doc/html/draft-harvey-cfrg-mtl-mode-07>.

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[RFC4034] Arends, R., Austein, R., Larson, M., Massey, D., and S. Rose, "Resource Records for the DNS Security Extensions", RFC 4034, DOI 10.17487/RFC4034, March 2005, <https://www.rfc-editor.org/info/rfc4034>.

[RFC4035] Arends, R., Austein, R., Larson, M., Massey, D., and S. Rose, "Protocol Modifications for the DNS Security Extensions", RFC 4035, DOI 10.17487/RFC4035, March 2005, <https://www.rfc-editor.org/info/rfc4035>.

[RFC6891] Damas, J., Graff, M., and P. Vixie, "Extension Mechanisms for DNS (EDNS(0))", STD 75, RFC 6891, DOI 10.17487/RFC6891, April 2013, <https://www.rfc-editor.org/info/rfc6891>.

[RFC8174] Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <https://www.rfc-editor.org/info/rfc8174>.

13.2. Informative References

[CTRSAMTL] Kaliski, B., Fregly, A.M., Harvey, J., and S. Sheth, "Merkle Tree Ladder Mode: Reducing the Size Impact of NIST PQC Signature Algorithms in Practice", 2023.

[MTL-ENDURANCE] Tran, M. and T. Chung, "Randomized Evaluation of SLH-DSA-MTL's Impact on Reducing PQ-DNSSEC Signature Sizes", 18 March 2025, <https://github.com/IQTF/pq-dnssec-materials/raw/refs/heads/main/IETF122/Tran_Randomized_evaluation_of_SLH-DSA-MTL's_impact_on_reducing_PQ-DNSSEC_signature_sizes.pdf>.

[NISTSELECTIONS] National Institute of Standards and Technology (NIST), "Status Report on the Third Round of the NIST Post-Quantum Cryptography Standardization Process", June 2022, <https://nvlpubs.nist.gov/nistpubs/ir/2022/NIST.IR.8413-upd1.pdf>.

[SPHINCSPLUS] Bernstein, D., Huelsing, A., Koelbl, S., Niederhagen, R., Rijneveld, J., and P. Schwabe, "The SPHINCS+ Signature Framework", Cryptology ePrint Archive, Report 2019/1086, 2019, <https://eprint.iacr.org/2019/1086.pdf>.

Appendix A. MTL Mode for DNSSEC Example

This appendix gives an example. The appendix also provides a step-by-step overview of how to verify an example condensed signature and an example full signature from the signed zone file. See [I-D.harvey-cfrg-mtl-mode] for additional details on the cryptographic operations.

In the following, byte strings are written in hexadecimal. For readability, a space or line break is inserted after each group of four bytes (eight hexadecimal characters). For example, the six-byte string with decimal byte values 1, 2, 4, 8, 16, 32 is written

01020408 1020

The function toByte(x,n) converts the integer x to a n-byte string, most significant byte first. (The function is defined in [FIPS205].) For example, toByte(16,4) produces the four-byte string

00000010

toByte assumes that 0 <= x <= 2^{8y}-1. This assumption holds in all calls to toByte within this appendix.

NOTE: For purposes of illustration we assigned the numeric DNSSEC algorithm identifier 50 for SLH-DSA-MTL-SHA2-128s. We plan to change to an experimental identifier in a future version of this draft, and before publishing any code for MTL mode for DNSSEC.

A.1. Initial Signed Zone File

The example zone file below includes several RRsets associated with the example.com zone. The SOA RRset has a full signature, while the A, AAAA, CNAME, MX, NS, NSEC3 and TXT RRsets each has a condensed signature. The DNSKEY RRset is unsigned. In practice, the DNSKEY RRset would be signed with a key signing key. We omitted this step for simplicity in this version of the draft. We plan to add sign the DNSKEY RRset with a MTL mode key signing key in the next version of the draft.

Any number of the signed RRsets in the zone file could have a full signature. We associated the full signature with the SOA record because the SOA record is updated whenever the zone changes. The condensed signatures on the other RRsets are all relative to the signed ladder in the full signature in the SOA RRSIG record. The corresponding full signature on an RRset can be formed by concatenating the condensed signature on the RRset with the signed ladder in the SOA RRSIG record’s full signature -- see Section 9.4 of [I-D.harvey-cfrg-mtl-mode]. As a result, a name server that loads this zone file can form a full signature on any of the RRsets when requested per Section 6 above, without access to the signer’s private key material.

The full signature is abridged in the example below. The complete value is given in Appendix A.6.

NOTE: The TXT record represented in the zone file below has been broken into two lines to fit in this Internet-Draft. Verifying the signature on the TXT record requires that the text (including spaces) match the source record which is a single line that reads: "This zone is an example input for SLH-DSA-MTL zone signing" with single spaces between each of the words.

```
example.com. 3600 IN SOA ns.example.com. admin.example.com. (
                            1719858941 7200 3600 1209600 3600 )
example.com. 3600 IN RRSIG SOA 50 2 3600 20250701183541 (
                            20240701183541 53939 example.com.
                            AWOXFesN5grvg1Vk/TE3ZNEAAEkgbrJ3DnyxAAA
                            AAgAAAAAAAAAHAANsVqmmBNLfHo2J8nnZz+kcir
                            50wSllXgmtilZzYqNXNtPjWTkxvxviqKtdIWEZh
                            hIAAEkgbrJ3DnyxAAIAAAAAAAAAB0wqgHBF0FWf
                            pS3J9JgTrXoAAAAIAAAACI ) # ... abridged
example.com. 3600 IN A 192.0.2.1
example.com. 3600 IN RRSIG A 50 2 3600 20250701183541 (
                            20240701183541 53939 example.com.
                            APnCCOkVSqjw6zKSPz40U6AAAEkgbrJ3DnyxAAA
                            AAAAAAAAAAAAHAAOGVodklRgciVyAG660gDJAS/
                            blgaqTfYU04u9LWETNe9PjWTkxvxviqKtdIWEZh
                            hI= )
example.com. 3600 IN NS ns1.example.net.
example.com. 3600 IN NS ns2.example.net.
example.com. 3600 IN RRSIG NS 50 2 3600 20250701183541 (
                            20240701183541 53939 example.com.
                            APVLlIBjy13ydSa9FxADHF4AAEkgbrJ3DnyxAAA
                            AAQAAAAAAAAAHAAN5pQH0FHJTRUCYkOBtwexgS/
                            blgaqTfYU04u9LWETNe9PjWTkxvxviqKtdIWEZh
                            hI= )
example.com. 3600 IN MX 10 mail.example.net.
example.com. 3600 IN RRSIG MX 50 2 3600 20250701183541 (
                            20240701183541 53939 example.com.
                            ALnLaReRJQiI5Zo1LcM/ajEAAEkgbrJ3DnyxAAA
                            AAwAAAAAAAAAHAAPO+30qRFTOs9aFxBzbQTVJir
                            50wSllXgmtilZzYqNXNtPjWTkxvxviqKtdIWEZh
                            hI= )
example.com. 3600 IN TXT "This zone is an example input for
                            SLH-DSA-MTL zone signing"
example.com. 3600 IN RRSIG TXT 50 2 3600 20250701183541 (
                            20240701183541 53939 example.com.
                            ADo++BxJN5KgDczdjzW9yyoAAEkgbrJ3DnyxAAA
                            ABAAAAAAAAAAHAANIBHbegIOSEdvxj8FpuwUhzg
                            KJmdG75STS6V/0/RqEvdINr1pRx28N2ClBwmX0j
                            wI= )
example.com. 3600 IN AAAA 2001:db8::1
example.com. 3600 IN RRSIG AAAA 50 2 3600 20250701183541 (
```

```
                                20240701183541 53939 example.com.
                                AIiR3ec5YTYyufoN4/m6mfcAAEkgbrJ3DnyxAAA
                                ABQAAAAAAAAAHAAMCqwQKN/jTi7+3gCImVZr9zg
                                KJmdG75STS6V/0/RqEvdINr1pRx28N2ClBwmX0j
                                wI= )
     example.com. 3600 IN DNSKEY 256 3 50 (
                                PawPGCKuykH6QOtfh6b8HoJZw4xMM+3QKvsTgo
                                T/5/8= ;{id = 53939 (zsk), size = 0b} )
     9vq38lj9qs6s1aruer131mbtsfnvek2p.example.com. 3600 IN NSEC3 1 0 (
                                1 -  0lverorlcjoa2lji5rik0otij3lgoj3l
                                A NS SOA MX TXT AAAA RRSIG DNSKEY )
     9vq38lj9qs6s1aruer131mbtsfnvek2p.example.com. 3600 IN RRSIG (
                                NSEC3 50 3 3600 20250701183541
                                20240701183541 53939 example.com.
                                AFLTit749Nqqdkh+etQwoDkAAEkgbrJ3DnyxAAA
                                ABgAAAAAAAAAHAAMDtIHLhQIPR4YdqvKF++jwvr
                                4HJ28uILKC7IXrGCYpWNINr1pRx28N2ClBwmX0j
                                wI= )
     www.example.com. 3600 IN CNAME example.com.
     www.example.com. 3600 IN RRSIG CNAME 50 3 3600 (
                                20250701183541 20240701183541 53939
                                example.com.
                                ABaMIKiaAl8rpjCN1unR9zgAAEkgbrJ3DnyxAAA
                                ABwAAAAAAAAAHAAODZdDLIaNHOsGFK2ydA637vr
                                4HJ28uILKC7IXrGCYpWNINr1pRx28N2ClBwmX0j
                                wI= )
     0lverorlcjoa2lji5rik0otij3lgoj3l.example.com. 3600 IN NSEC3 1 0 (
                                1 -  9vq38lj9qs6s1aruer131mbtsfnvek2p
                                CNAME RRSIG )
     0lverorlcjoa2lji5rik0otij3lgoj3l.example.com. 3600 IN RRSIG (
                                NSEC3 50 3 3600 20250701183541
                                20240701183541 53939 example.com.
                                AD3B1TW3oNgurikkoA+mxSgAAEkgbrJ3DnyxAAA
                                ACAAAAAgAAAAIAAA= )
```

A.2. Obtaining the Public Key

As usual in DNSSEC, the verifier obtains the public key for verifying signatures from the DNSKEY RRset (which in this example includes only one record):

```
  example.com. 3600 IN DNSKEY 256 3 50 (
                                PawPGCKuykH6QOtfh6b8HoJZw4xMM+3QKvsTgo
                                T/5/8= ; key id = 53939 )
```

Following Section 2.2 of [RFC4034], the RDATA portion of this record (the fields to the right of "DNSKEY") includes the following fields:

* Flag: 256 (zone key bit = 1)
* Protocol: 3 (fixed value)
* Algorithm: 50 (SLH-DSA-MTL-SHA2-128s)
* Public Key: PawPGCKuykH6QOtfh6b8HoJZw4xMM+3QKvsTgoT/5/8= [44 characters in Base64]

The key tag for this public key, as shown in the comments, is 53939 (decimal). (The key tag is computed from the public key following Appendix B of [RFC4034].) The Base64 value of the Public Key field corresponds to the following byte string:

```
3DAC0F18 22AECA41 FA40EB5F 87A6FC1E
8259C38C 4C33EDD0 2AFB1382 84FFE7FF [32 bytes]
```

The verifier parses the byte string following [FIPS205] to obtain the public key components:

```
3DAC0F18 22AECA41 FA40EB5F 87A6FC1E - PK.seed [16 bytes]
8259C38C 4C33EDD0 2AFB1382 84FFE7FF - PK.root [16 bytes]
```

A.3. Verifying a Condensed Signature

This section illustrates how the example A RRSIG record can be verified. Other RRSIG records with condensed signatures can be verified similarly. The example A RRSIG record is:

```
example.com. 3600 IN RRSIG A 50 2 3600 20250701183541 (
                            20240701183541 53939 example.com.
                            APnCCOkVSqjw6zKSPz40U6AAAEkgbrJ3DnyxAAA
                            AAAAAAAAAAAAHAAOGVodklRgciVyAG660gDJAS/
                            blgaqTfYU04u9LWETNe9PjWTkxvxviqKtdIWEZh
                            hI= )
```

Following Section 3.2 of [RFC4034], the RDATA portion of this record includes the following fields:

* Type Covered: A
* Algorithm: 50 (SLH-DSA-MTL-SHA2-128s)
* Labels: 2
* Original TTL: 3600 seconds
* Signature Expiration: 1 July 2025 18:35:41 UTC
* Signature Inception: 1 July 2024 18:35:41 UTC
* Key Tag: 53939
* Signer’s Name: "example.com."
* Signature: APnCCOkVSqjw6zKSPz40U6AAAEkgbrJ3DnyxAAAAAAAAAAAAAAAAHAAO GVodklRgciVyAG660gDJAS/blgaqTfYU04u9LWETNe9PjWTkxvxviqKtdIWEZhhI= [120 characters in Base64]

The Base64 value of the Signature field corresponds to the following byte string:

```
00F9C208 E9154AA8 F0EB3292 3F3E3453 A0000049 206EB277
0E7CB100 00000000 00000000 00000700 03865687 6495181C
895C801B AEB48032 404BF6E5 81AA937D 8534E2EF 4B5844CD
7BD3E359 3931BF1B E2A8AB5D 21611986 12 [89 bytes]
```

Per Section 4 of this document, the initial 00 byte of the byte string indicates that the signature is in condensed format. The remaining 88 bytes are the condensed signature.

A.3.1. Parsing the Condensed Signature

The verifier parses the condensed signature to obtain the randomizer, the series identifier, the authentication path and other information following Section 9.5 of [I-D.harvey-cfrg-mtl-mode].

For the example A RRSIG record, the parsing produces these fields:

Randomizer

```
F9C208E9 154A8F0 EB32923F 3E3453A0 - randomizer R_mtl [16 bytes]
```

Authentication Path

```
0000 - flags (must be 0 per [I-D.harvey-cfrg-mtl-mode]) [2 bytes]
49206EB2 770E7CB1 - series identifier SID [8 bytes]
00000000 - leaf index: i = 0 [4 bytes]
00000000 - rung left index: 0 [4 bytes]
00000007 - rung right index: 7 [4 bytes]
0003 - sibling hash count: 2 [2 bytes]
    Sibling node hash values
86568764 95181C89 5C801BAE B4803240 - V[1:1] [16 bytes]
4BF6E581 AA937D85 34E2EF4B 5844CD7B - V[2:3] [16 bytes]
D3E35939 31BF1BE2 A8AB5D21 61198612 - V[4:7] [16 bytes]
```

The authentication path for this signature connects the leaf node hash value V[0:0] to the ladder rung V[0:7] (see Appendix A.4.1). The sibling node hash values are denoted V[1:1], V[2:3] and V[4:7]. (In an implementation, a verifier may receive an authentication path with a different number of hash values and/or different actual values than the signer intended. The authentication path verification operation, e.g., Section 8.8 of [I-D.harvey-cfrg-mtl-mode], would check that both the number and values are correct.)

A.3.2. Forming the MTL Mode Message Input

The verifier forms the message input M[i] to the MTL mode verification operation following DNSSEC conventions specified in Section 3.1.8.1 of [RFC4034]: it is the concatenation of the wire format of the RDATA portion of the associated RRSIG record excluding the Signature field, and the wire format of the associated RRset. The value produced by this step for the example A RRset and its associated RRSIG record is:

```
M[0] = 00013202 00000E10 68642A7D 6682F6FD D2B30765 78616D70
       6C650363 6F6D0007 6578616D 706C6503 636F6D00 00010001
       00000E10 0004C000 0201 [58 bytes]
```

NOTE: For cryptography implementers not familiar with DNSSEC, the message bytes of M[0] can be parsed as follows:

RDATA portion of RRSIG (excluding Signature field) wire format

```
0001 - Type Covered: 1 (A) [2 bytes]
32 - Algorithm: 50 (SLH-DSA-MTL-SHA2-128s) [1 byte]
02 - Labels: 2 [1 byte]
00000E10 - Original TTL:  3600 seconds [4 bytes]
68642A7D - Sig Expiration: 1 July 2025 18:35:41 UTC [4 bytes]
6682F6FD - Sig Inception: 1 July 2024 18:35:41 UTC  [4 bytes]
D2B3 - Key Tag: 53939 [2 bytes]
07657861 6D706C65 03636F6D 00 - Signer’s Name:
                                "example.com." [variable]
```

RRset wire format

```
07657861 6D706C65 03636F6D 00 - Owner Name:
                                "example.com." [variable]
0001 - Type:  1 (A) [2 bytes]
0001 - Class:  1 (IN) [2 bytes]
00000E10 - Time to Live:  3600 seconds [4 bytes]
0004 - length in bytes of RDATA portion: 4 [2 bytes]
C0000201 - RDATA portion: Host Address (192.0.2.1) [4 bytes]
```

A.3.3. Computing the Leaf Node Hash Value

The verifier computes the leaf node hash value V[i] from the message M[i], the per-message randomizer R_mtl[i] and certain other information following Sections 5.1 and 8.2.1 of [I-D.harvey-cfrg-mtl-mode]. The process has two steps:

* Hash the message M[i] together with the randomizer R_mtl[i], the public key seed PK.seed, the public key root PK.root, and an address field to obtain a data value d[i] following Section 5.1 of [I-D.harvey-cfrg-mtl-mode]
* Hash the data value d[i] together the public key seed PK.seed and a compressed address field to obtain a leaf node hash value V[i] following Section 8.2.1 of [I-D.harvey-cfrg-mtl-mode]

For SLH-DSA-MTL-SHA2-128s, the steps simplify to the following operations:

```
ADRS[i] = toByte(0,8) || SID || toByte(16,4) || toByte(0,8) ||
          toByte (i,4)
d[i] = MGF1-SHA2-256 (R_mtl[i] || PK.seed || SHA2-256 (R_mtl[i] ||
          PK.seed || PK.root || toByte(128,1) || toByte (0,1) ||
          ADRS[i] || M[i]), 16)
ADRS^c[i] = toByte(0,1) || SID || toByte(17,1) || toByte(0,8) ||
          toByte (i,4)
V[i] = SHA2-256 (PK.seed || toByte(0,48) || ADRS^c[i] || d[i])
          truncated to the first 16 bytes
```

The leaf node hash value V[i] is alternatively denoted V[i:i] when input to the internal node hash value operations in the next section.

For the example record, the values involved are:

```
SID = 49206EB2 770E7CB1 [8 bytes]
ADRS[0] = 00000000 00000000 49206EB2 770E7CB1
          00000010 00000000 00000000 00000000 [32 bytes]
R_mtl[0] = F9C208E9 154AA8F0 EB32923F 3E3453A0 [16 bytes]
PK.seed = 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E [16 bytes]
PK.root = 8259C38C 4C33EDD0 2AFB1382 84FFE7FF [16 bytes]
M[0] = 00013202 00000E10 68642A7D 6682F6FD D2B30765 78616D70
       6C650363 6F6D0007 6578616D 706C6503 636F6D00 00010001
       00000E10 0004C000 0201 [58 bytes]
SHA-256 input within MGF1-SHA2-256 call = F9C208E9 154AA8F0
       EB32923F 3E3453A0 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E
       8259C38C 4C33EDD0 2AFB1382 84FFE7FF 80000000 00000000
       00004920 6EB2770E 7CB10000 00100000 00000000 00000000
       00000001 32020000 0E106864 2A7D6682 F6FDD2B3 07657861
       6D706C65 03636F6D 00076578 616D706C 6503636F 6D000001
       00010000 0E100004 C0000201  [140 bytes]
SHA-256 full output within MGF1-SHA-256 call = 020D9241 F02420F6
       5855C6AA DAA82B18 F9F4E13E 78BF6C63 7ABA745A 593B5DB4
       [32 bytes]
MGF1-SHA-256 input = F9C208E9 154AA8F0 EB32923F 3E3453A0 3DAC0F18
       22AECA41 FA40EB5F 87A6FC1E 020D9241 F02420F6 5855C6AA
       DAA82B18 F9F4E13E 78BF6C63 7ABA745A 593B5DB4 [64 bytes]
d[0] = MGF1-SHA2-256 output = 3564B082 F8E79D9D 31B8BA7C B05E9EB7
       [16 bytes]
ADRS^c[0] = 0049206E B2770E7C B1110000 00000000 00000000 0000
       [22 bytes]
SHA2-256 input for V[0] = 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E
       00000000 00000000 00000000 00000000 00000000 00000000
       00000000 00000000 00000000 00000000 00000000 00000000
       0049206E B2770E7C B1110000 00000000 00000000 00003564
       B082F8E7 9D9D31B8 BA7CB05E 9EB7 [102 bytes]
V[0:0] = V[0] = SHA2-256 output truncated to 16 bytes = 79A501F4
       14725345 409890E0 6DC1EC60 [16 bytes]
```

Note. The simplified operations given above for SLH-DSA-MTL-SHA2-128s can be derived from [I-D.harvey-cfrg-mtl-mode] as follows:

1. The address value ADRS[i] has type MTL_MSG = 16 per Section 4.6 of [I-D.harvey-cfrg-mtl-mode].
2. The randomized hash function H_mtl_msg is the MGF1-SHA2-256 / SHA-256 combination defined in Section 10.2.1 of [I-D.harvey-cfrg-mtl-mode]. The output of the call to SHA2-256 within this combination is not truncated; it remains 32 bytes when input to MGF1-SHA2-256.
3. The message input to H_mtl_msg is a message domain separator of type MTL_MSG_SEP = 128 with an empty context string, followed by ADRS[i], followed by the actual message M[i], per Section 5.1 of [I-D.harvey-cfrg-mtl-mode].

4. The compressed address value ADRS^c[i] has type MTL_DATA = 17 per Section 4.6 of [I-D.harvey-cfrg-mtl-mode].
5. The leaf node hash function F is SHA2-256 where PK.seed is padded with zeroes on the right to 64 bytes per Section 10.2.3 of [I-D.harvey-cfrg-mtl-mode].

A.3.4. Checking the Authentication Path

The verifier checks the authentication path from the leaf node hash value V[i:i] to a ladder rung following Section 8.8 of [I-D.harvey-cfrg-mtl-mode]. The ladder rung is obtained separately, either by requesting a full signature on the same RRset as described in Section 6 of this document (see also Appendix A.1), or from a full signature previously requested (and remembered) for a different RRset.

The authentication path checking process involves one or more iterations of this step:

* Hash a left node hash value and a right node hash value together with the public key seed PK.seed and an address field to obtain an internal node hash value

For SLH-DSA-MTL-SHA2-128s, the step simplifies to one or more operations of the following form:

* ADRS^c[L:R] = toByte(0,1) || SID || toByte(18,1) || toByte(0,4) || toByte (L,4)|| toByte (R,4)
* V[L:R] = SHA2-256 (PK.seed || toByte(0,48) || ADRS^c[L:R] || V[L:M-1] || V[M:R]) truncated to the first 16 bytes

Here, V[L:R] is the internal node hash value being computed and V[L:M-1] and V[M:R] are its child left and right node hash values. Following [I-D.harvey-cfrg-mtl-mode], M is the unique integer between L+1 and R that is divisible by the largest power of two.

For the example record, the process involves two iterations (following the Merkle node set structure in Appendix A.5.2 from leaf to rung):

* Hash V[0:0] and V[1:1] together with PK.seed and an address field to obtain V0:1 (L = 0, R = 1, M = 1)
* Hash V[0:1] and V[2:3] together with PK.seed and an address field to obtain V0:3 (L = 0, R = 3, M = 2)
* Hash V[0:3] and V[4:7] together with PK.seed and an address field to obtain V0:7 (L = 0, R = 7, M = 4)

V[0:0] = V[0] was computed in Appendix A.3.3, while V[0:1], V[2:3] and V[4:7] were obtained from the authentication path in Appendix A.3.1.

The values involved are:

```
SID = 49206EB2 770E7CB1 [8 bytes]
ADRS^c[0:1] = 0049206E B2770E7C B1120000 00000000 00000000 0001
              [22 bytes]
PK.seed = 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E [16 bytes]
V[0:0] = 79A501F4 14725345 409890E0 6DC1EC60 [16 bytes]
V[1:1] = 86568764 95181C89 5C801BAE B4803240 [16 bytes]
SHA2-256 input = 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E 00000000
              00000000 00000000 00000000 00000000 00000000 00000000
              00000000 00000000 00000000 00000000 00000000 0049206E
              B2770E7C B1120000 00000000 00000000 000179A5 01F41472
              53454098 90E06DC1 EC608656 87649518 1C895C80 1BAEB480
              3240 [118 bytes]
V[0:1] = SHA-256 output truncated to 16 bytes = 8ABE74C1 29655E09
              AD8A5673 62A35736 [16 bytes]
ADRS^c[2:3] = 0049206E B2770E7C B1120000 00000000 00000002 0003
              [22 bytes]
V[2:3] = 4BF6E581 AA937D85 34E2EF4B 5844CD7B [16 bytes]
SHA2-256 input = 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E 00000000
              00000000 00000000 00000000 00000000 00000000 00000000
              00000000 00000000 00000000 00000000 00000000 0049206E
              B2770E7C B1120000 00000000 00000000 00038ABE 74C12965
              5E09AD8A 567362A3 57364BF6 E581AA93 7D8534E2 EF4B5844
              CD7B [118 bytes]
V[0:3] = SHA2-256 output truncated to 16 bytes = D20DAF5A 51C76F0D
              D82941C2 65F48F02 [16 bytes]
ADRS^c[4:7] = 0049206E B2770E7C B1120000 00000000 00000004 0007
              [22 bytes]
V[4:7] = D3E35939 31BF1BE2 A8AB5D21 61198612 [16 bytes]
SHA2-256 input = 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E 00000000
              00000000 00000000 00000000 00000000 00000000 00000000
              00000000 00000000 00000000 00000000 00000000 0049206E
              B2770E7C B1120000 00000000 00000000 0007D20D AF5A51C7
              6F0DD829 41C265F4 8F02D3E3 593931BF 1BE2A8AB 5D216119
              8612 [118 bytes]
V[0:7] = SHA2-256 output truncated to 16 bytes = 4C2A8070 45D0559F
              A52DC9F4 9813AD7A [16 bytes]
```

Figure 1

The internal node hash value V[0:7] matches the corresponding rung in the ladder (see Appendix A.4.1), so the authentication path is verified.

Note. The simplified operations given above for SLH-DSA-MTL-SHA2-128s can be derived from [I-D.harvey-cfrg-mtl-mode]as follows:

1. The compressed address value ADRS^c[i] has type MTL_TREE = 18 as defined in Section 4.6 of [I-D.harvey-cfrg-mtl-mode].
2. The leaf node hash function H is SHA-256 where PK.seed is padded with zeroes on the right to 64 bytes, as defined in Section 10.2.3 of [I-D.harvey-cfrg-mtl-mode].

A.4. Verifying a Full Signature

The RRSIG record for the example SOA RRset includes a full signature. The abridged Base64 value of the signature field of the RRSIG record is:

```
AWOXFesN5grvg1Vk/TE3ZNEAAEkgbrJ3DnyxAAAAAgAAAAAAAAAHAANsVqmmBNLfHo2
J8nnZz+kcir50wSllXgmtilZzYqNXNtPjWTkxvxviqKtdIWEZhhIAAEkgbrJ3DnyxAA
IAAAAAAAAAB0wqgHBF0FWfpS3J9JgTrXoAAAAIAAAACIqAre8NNFy48Tcs96QkJKAAA
B6w3N7mZva9FQDM ...
```

This value corresponds to the following abridged byte string:

```
01639715 EB0DE60A EF835564 FD313764 D1000049 206EB277
0E7CB100 00000200 00000000 00000700 036C56A9 A604D2DF
1E8D89F2 79D9CFE9 1C8ABE74 C129655E 09AD8A56 7362A357
36D3E359 3931BF1B E2A8AB5D 21611986 12000049 206EB277
0E7CB100 02000000 00000000 074C2A80 7045D055 9FA52DC9
F49813AD 7A000000 08000000 088A80AD EF0D345C B8F1372C
F7A42424 A000001E B0DCDEE6 66F6BD15 00CC ...
```

The complete Base64 value and byte string are given in Appendix A.6. Per Section 4 of this document, the initial 01 byte of this string indicates that the signature is in full format. The remaining 7856 bytes are the full signature.

A.4.1. Parsing the Full Signature

The verifier parses the full signature to obtain the randomizer, the series identifier, the authentication path, the ladder, the underlying signature on the ladder and other information following Section 9.4 of [I-D.harvey-cfrg-mtl-mode].

For the example record, the parsing produces these fields:

Randomizer

```
639715EB 0DE60AEF 835564FD 313764D1 - randomizer R_mtl [16 bytes]
```

Authentication Path

```
0000 - flags (must be 0 per [I-D.harvey-cfrg-mtl-mode]) [2 bytes]
49206EB2 770E7CB1 - series identifier SID [8 bytes]
00000002 - leaf index: i = 2 [4 bytes]
00000000 - rung left index: 0 [4 bytes]
00000007 - rung right index: 7 [4 bytes]
0003 - sibling hash count: 2 [2 bytes]
      Sibling node hash values
6C56A9A6 04D2DF1E 8D89F279 D9CFE91C - V[3:3] [16 bytes]
8ABE74C1 29655E09 AD8A5673 62A35736 - V[0:1] [16 bytes]
D3E35939 31BF1BE2 A8AB5D21 61198612 - V[4:7] [16 bytes]
```

Ladder

```
0000 - flags (must be 0 per [I-D.harvey-cfrg-mtl-mode]) [2 bytes]
49206EB2 770E7CB1 - series identifier SID [8 bytes]
0002 - rung count: 2 [4 bytes]
00000000 - rung left index: 0 [4 bytes]
00000007 - rung right index: 7 [4 bytes]
4C2A8070 45D0559F A52DC9F4 9813AD7A - rung hash V[0:7] [16 bytes]
00000008 - rung left index: 8 [4 bytes]
00000008 - rung right index: 8 [4 bytes]
8A80ADEF 0D345CB8 F1372CF7 A42424A0 - rung hash V[8:8] [16 bytes]
```

Signature on ladder

```
00001EB0 - length in bytes of underlying signature: 7856 [4 bytes]
DCDEE666 F6BD1500 CC ...  - underlying signature
```

The authentication path for this signature connects the leaf node hash value V[2:2] to the ladder rung V[0:7]. The sibling node hash values are therefore assumed to be V[3:3], V[0:1] and V[4:7]. (See Appendix A.3.1)

The rungs included in the ladder are V[0:7] and V[8:8].

The values produced by this step are:

```
i =  2
R_mtl[2] =  639715EB 0DE60AEF 835564FD 313764D1 [16 bytes]
SID =  49206EB2 770E7CB1 [8 bytes]
V[3:3] =  6C56A9A6 04D2DF1E 8D89F279 D9CFE91C [16 bytes]
V[0:1] =  8ABE74C1 29655E09 AD8A5673 62A35736 [16 bytes]
V[4:7] =  D3E35939 31BF1BE2 A8AB5D21 61198612 [16 bytes]
ladder =  00004920 6EB2770E 7CB10002 00000000 00000007 4C2A8070
   45D0559F A52DC9F4 9813AD7A 00000008 00000008 8A80ADEF 0D345CB8
   F1372CF7 A42424A0 [60 bytes]
```

V[0:7] = 4C2A8070 45D0559F A52DC9F4 9813AD7A [16 bytes]
V[8:8] = 8A80ADEF 0D345CB8 F1372CF7 A42424A0 [16 bytes]
underlying signature on ladder (abridged) = DCDEE666 F6BD1500 CC ...
[7856 bytes]

A.4.2. Verifying the Underlying Signature

The verifier verifies the underlying signature on the ladder following Section 9.2 of [I-D.harvey-cfrg-mtl-mode].

For SLH-DSA-MTL-SHA2-128s, the steps simplify to the following operation:

* Verify the underlying signature on the byte string toByte(129,1) || toByte(0,1) || ladder using SLH-DSA-SHA2-128s's internal verification operation.

The details of SLH-DSA-SHA2-128s are not included here.

For the example record, the values involved are:

* message input = 81000000 49206EB2 770E7CB1 00020000 00000000 00074C2A 807045D0 559FA52D C9F49813 AD7A0000 00080000 00088A80 ADEF0D34 5CB8F137 2CF7A424 24A0 [62 bytes]
* underlying signature (abridged) = DCDEE666 F6BD1500 CC ... [7856 bytes]
* public key input = 3DAC0F18 22AECA41 FA40EB5F 87A6FC1E 8259C38C 4C33EDD0 2AFB1382 84FFE7FF [32 bytes]

Once the signature on the ladder is verified, the rungs of the ladder can be used to verify authentication paths, e.g., as in Appendix A.3.4.

Note. The simplified operation given above for SLH-DSA-MTL-SHA2-128s can be derived from [I-D.harvey-cfrg-mtl-mode] as follows:

1. The message input to SLH-DHA-SHA-128s's internal verification operation is the ladder prepended with a domain separator of type MTL_LADDER_SEP = 129 and a context string length of 0, following Section 9.2 of [I-D.harvey-cfrg-mtl-mode]. (The context string is empty.)

A.4.3. Forming the Message, Computing the Leaf Node Hash Value and Checking the Authentication Path

These steps are the same as in Sections A.2.2, A.2.3 and A.2.4 for condensed signatures.

A.5. How the Example Signed Zone File was Generated

A.5.1. Generating the Signed Zone File

We started with the following unsigned zone file:

```
example.com. IN SOA ns.example.com. admin.example.com. 1719172701 (
                            7200 3600 1209600 3600 )
example.com. IN A 192.0.2.1
example.com. IN AAAA 2001:db8::1
example.com. IN MX 10 mail.example.net.
example.com. IN TXT "This zone is an example input for SLH-DSA-MTL
                            zone signing"
www.example.com. IN CNAME example.com.
example.com. IN NS ns1.example.net.
example.com. IN NS ns2.example.net.
```

The zone file includes seven RRsets. We added two NSEC3 records to provide proof of the non-existence of other RRtypes for example.com and of www.example.com, and of other domain names in the zone, bringing the number of RRsets to be signed to nine. As mentioned in Appendix A.1, we did not sign the DNSKEY RRset.

We generated a new SLH-DSA-MTL-SHA2-128s public key / private key pair. The public key is the one in Appendix A.1.

We decided to sign all nine non-DNSKEY RRsets in a single message series. We also decided to order the messages within the series according to the canonical order of the domain names per [RFC4034] (example.com followed by www.example.com) and within a given domain name, by the numeric values of the RRtypes:

* A (1)
* NS (2)
* SOA (6)
* MX (15)
* TXT (16)
* AAAA (28)
* NSEC3 (50)

Implementations may group and order the messages differently.

For the single message series, we generated the series identifier SID = 49206EB2 770E7CB1.

For each RRset message M[i], we then performed the following steps:

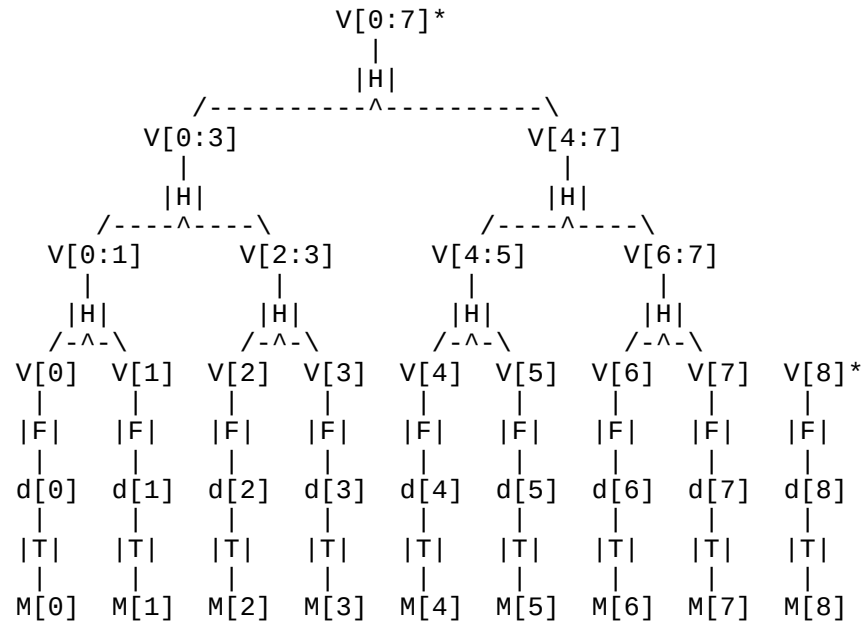
* We formed the messages M from the RRset and the RDATA portion of the anticipated RRSIG record excluding the Signature field following Appendix A.3.2.
* We computed a randomizer R_mtl[i] following Section 5.1 of [I-D.harvey-cfrg-mtl-mode]. (The details of this step are omitted for simplicity.)
* We computed a leaf node hash value V[i] from the message M[i], the randomizer R_mtl[i] and certain other inputs following Appendix A.3.3.

As we computed the leaf node hash values, we also computed internal node hash values in the Merkle node set following the same hashing steps as for checking authentication paths in Appendix A.3.4. We then formed a Merkle tree ladder from the internal node hash values following the binary rung strategy in [I-D.harvey-cfrg-mtl-mode] and signed the ladder with the SLH-DSA-MTL-SHA2-128s private key.

We next formed condensed signatures to be included in the RRSIG records associated with each of the messages being signed, other than the SOA record. We finally formed a full signature to be included in the RRSIG record associated with the SOA record.

A.5.2. Merkle Node Set Structure

The nine-message series that we signed produced a Merkle node set with the structure shown below. Following the binary rung strategy, the node set includes two binary trees: an eight-leaf tree with root hash value V[0:7] and a one-leaf tree with root hash value V[8:8]. In the diagram, an asterisk indicates that a node hash value is a rung in the Merkle tree ladder. The symbol T is shorthand for the H_msg_mtl function call. For simplicity, the randomizers and other inputs to the functions H, F and H_msg_mtl are not shown.



A.6. Full Signature

The full signature byte string is: 01639715 EB0DE60A EF835564
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Appendix B. Change Log

00: Initial draft of the document.
01: Update expiration of document
02: Add appendix with example of MTL Mode signatures in DNSSEC
03: Update draft to align with FIPS-205
04: Updated the implementation status section with links to known implementations
05: Added the implementation considerations section on batch signing

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