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Stateless Hash-Based Signatures in Merkle Tree Ladder Mode (SLH-DSA-MTL)  
for DNSSEC  
draft-fregly-dnsop-slh-dsa-mtl-dnssec-04

## 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.

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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-model]. 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-model], 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-model]. 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-model]:

```

          1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 3 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-----+-----+-----+-----+-----+-----+-----+-----+
|  MTL-Type  |                                         |
+-----+-----+-----+-----+-----+-----+-----+-----+
|                                         SLH-DSA-MTL-SHA2-128s signature                                         |
/                                                                                               /
/                                                                                               /
+-----+-----+-----+-----+-----+-----+-----+-----+

```

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-model]:

```

          1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 3 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-----+-----+-----+-----+-----+-----+-----+-----+
|  MTL-Type  |                                         |
+-----+-----+-----+-----+-----+-----+-----+-----+
|                                         SLH-DSA-MTL-SHAKE-128s signature                                         |
/                                                                                               /
/                                                                                               /
+-----+-----+-----+-----+-----+-----+-----+-----+

```

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-model]. 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:

```

0                               8                               16
+-----+-----+-----+-----+-----+-----+-----+-----+
|                               OPTION-CODE                               |
+-----+-----+-----+-----+-----+-----+-----+-----+
|                               OPTION-LENGTH                             |
+-----+-----+-----+-----+-----+-----+-----+-----+

```

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

TBD

## 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-06, 15 March 2025, <<https://datatracker.ietf.org/doc/html/draft-harvey-cfrg-mtl-mode-06>>.
- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <<https://www.rfc-editor.org/info/rfc2119>>.
- [RFC4033] Arends, R., Austein, R., Larson, M., Massey, D., and S. Rose, "DNS Security Introduction and Requirements", RFC 4033, DOI 10.17487/RFC4033, March 2005, <<https://www.rfc-editor.org/info/rfc4033>>.
- [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.

## [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](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  $0 \leq x \leq 2^{\{8y\}} - 1$ . 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/TE3ZNEAAEkgrJ3DnyxAAA
    AAgAAAAAAAAAHAANsVqmmBNLfHo2J8nnZz+kcir
    50wS1lXgmtilZzYqNXNtPjWTkxvxiqKtdIWEZh
    hIAAEkgbrJ3DnyxAAIAAAAAAAAAAB0wqgHBF0FWf
    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
    AAAAAAAAAAAHAAOGVodklRgciVyAG660gDJAS/
```

```
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.
APVLLlIBjy13ydSa9FxADHF4AAEkGbrJ3DnyxAAA
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.
ALnLaReRJQiI5ZolLcM/ajEAAEkGbrJ3DnyxAAA
AAwAAAAAAAAAHAAP0+30qRFT0s9aFxBzbQTVJir
50wS1lXgmtilZzYqNXNtPjWTKxvXviqKtdIWEZh
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
ABAAAAAAAAAHAANIBHbegIOSEdVxj8FpuwUhZg
KJmdG75STS6V/0/RqEvdINrlpRx28N2ClBwmX0j
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+3gCI mVZr9zg
KJmdG75STS6V/0/RqEvdINrlpRx28N2ClBwmX0j
wI= )
example.com. 3600 IN DNSKEY 256 3 50 (
PawPGCKuykH6Q0tfh6b8HoJZw4xMM+3QKvsTgo
T/5/8= ;{id = 53939 (zsk), size = 0b} )
9vq38lj9qs6slaruer13lmbtsfnvek2p.example.com. 3600 IN NSEC3 1 0 (
1 - 0lverorlcjoa2lji5rik0otij3lgoj3l
A NS SOA MX TXT AAAA RRSIG DNSKEY )
9vq38lj9qs6slaruer13lmbtsfnvek2p.example.com. 3600 IN RRSIG (
NSEC3 50 3 3600 20250701183541
20240701183541 53939 example.com.
AFLTit749Nqqdkh+etQwoDkAAEkGbrJ3DnyxAAA
ABgAAAAAAAAAHAAMDtIHLhQIPR4YdqvKF++jwvr
4HJ28uILKC7IXrGCYpWNINrlpRx28N2ClBwmX0j
wI= )
www.example.com. 3600 IN CNAME example.com.
www.example.com. 3600 IN RRSIG CNAME 50 3 3600 (
20250701183541 20240701183541 53939
```

```

example.com.
ABaMIKiaA18rpjCN1unR9zgAAEkqbrJ3DnyxAAA
ABwAAAAAAAAAHAAODZdDLIaNHOSGFK2ydA637vr
4HJ28uILKC7IXrGCYpWNINr1pRx28N2ClBwmX0j
wI= )
0lverorlcjoa2lji5rik0otij3lgoj3l.example.com. 3600 IN NSEC3 1 0 (
1 - 9vq38lj9qs6slaruer13lmbtsfnvek2p
CNAME RRSIG )
0lverorlcjoa2lji5rik0otij3lgoj3l.example.com. 3600 IN RRSIG (
NSEC3 50 3 3600 20250701183541
20240701183541 53939 example.com.
AD3B1TW3oNgurikkoA+mxSgAAEkqbrJ3DnyxAAA
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
                                AAAAAAAAAAAAAHAAOGVodklRgciVyAG660gDJAS/
                                blgaqTfYU04u9LWETNe9PjWtkxvxviqKtdIWEZhhI=
                                )
```

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-model]) [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-model], 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-model] as follows:

1. The compressed address value  $\text{ADRS}^c[i]$  has type `MTL_TREE = 18` as defined in Section 4.6 of [I-D.harvey-cfrg-mtl-model].
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-model].

#### 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/TE3ZNEAAEkgrJ3DnyxAAAAAgAAAAAAAAAHAANsVqmmBNLfHo2
J8nnZz+kcir50wSllXgmtilZzYqNXNtPjWTkxvxiqKtdIWEZhhIAAEkgbrJ3DnyxAA
IAAAAAAAAAAB0wqgHBF0FWfpS3J9JgTrXoAAAAIAAAACIqAre8NNFy48Tcs96QkJKAAA
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-model] 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-model]. (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:

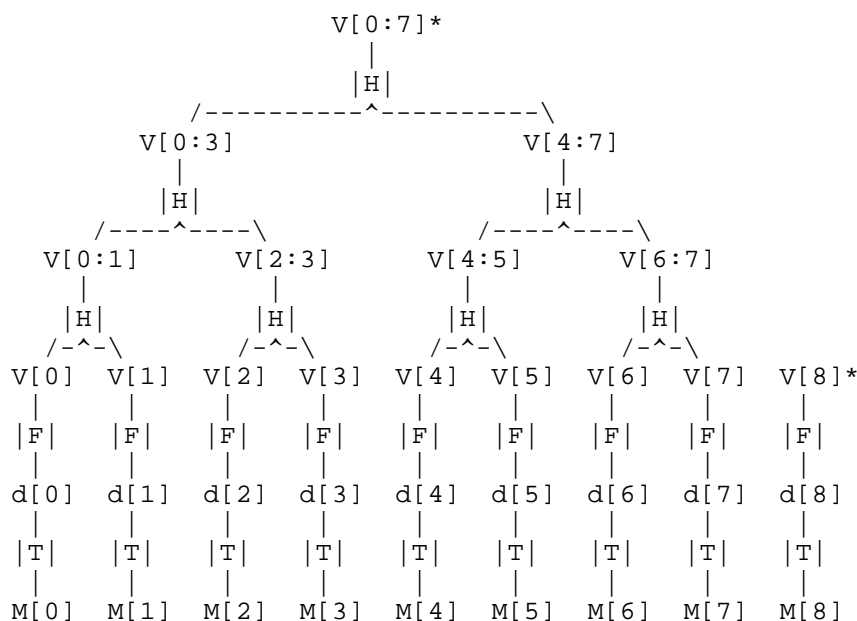
- \* We formed the messages  $M$  from the RRset and the RDATA portion of the anticipated RRSIG record excluding the Signature field following Appendix A.3.2.
- \* We computed a randomizer  $R\_mtl[i]$  following Section 5.1 of [I-D.harvey-cfrg-mtl-mode]. (The details of this step are omitted for simplicity.)
- \* 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  
 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 00CC8B96 E8A56A67 C13C4325 08C3C29D FFD98566  
 37C4B60D 6874508C 078363C1 48CCE173 179DCCDB 06A08E5E 2FC65C12  
 0D39141F 7ABFAEF0 7CEFA113 595CA3EA 1B696C57 7984E4E4 25A35556  
 09C9F105 F11246E1 A2DD2286 006D0267 B13C72CB 765400E0 09F40283  
 211D7576 632836A7 F0240FE8 33FCC73D B067E874 DE4D53BE 3B74AE9B  
 2AFD2820 B60F0BB1 0373C958 7A627B38 9E7F9CE0 2241709C 2BE68B7A  
 4FC70EA4 2218743C 0023BADF 2264709F 41428E0E 1D7AD877 8330E058

899E7A3F 2415E5BF 811796EB 97A71BAA 8D21EAAD 6EE15C7D B79E2145  
B0DE85BC 97B71121 E2F86C90 9A445950 651C973C E18B25CF 07D779BA  
2A0C43C3 51A1B24C 3E6FAAD8 A5599D9E 12260856 F9C7F132 2F9BD297  
1A5CF48C 58F87AF9 028C1CCF EBCBDA83 5DCB04C5 B794CCED 43D40963  
EBD56F47 35D9B36F FFE2B144 85C2EA40 020FE108 455AF337 8FED7569  
EF6278F4 B048C391 5F17DA4E EF01E77B D585007E F34C14D5 BE41ADA1  
24AAAAB1 02D6662E 05D45915 8B81FBBB 0D07F2E4 9A32CAF6 4E6EB3D3  
318BFBAF 3576547D B258D910 73074D28 1E3F1E9F 08F3C498 09691724  
0CC6F09A D2BEA46F 67491B27 6A03F40D 600877CA 2709E914 94004FCD  
8E500B3B C441456D 3D6CC46C 31B91968 E255BE46 21C6C75A BE21FA7A  
99897481 8F0C57D4 A7B385ED 10A9559C CC88AE68 25899BCE 15AF960D  
37B3884A 1351FD87 92912F2C C3EBC824 B06BEAF2 41B5972F 05C5EC6B  
5C346D01 D935D75E 887A0590 57B85893 BA879ED2 1B135A47 048DB9BC  
7C10CC1C D596C675 C3C2DC29 2BF3A0CE A48DAA7F 6F23D0E4 1405FDE0  
F04B4BA8 F7E80AD9 435306CF 2B8AE120 D638B29C C3146515 CFE4855E  
91F604C4 C6DE4C41 54DEB6F7 2CCDCDDE 5E247B71 795ADB25 8CCEE545  
A9AC0013 B2C68822 3665DB45 A6328361 B19B6B22 27982D95 8FE46979  
A058665A DDBE64A8 8D7C4E12 3BCA8792 A89DC673 6D6AE4A9 81909EE3  
DBD5482B 44FD9552 48A220CD 629E5E42 1934C4D5 205BFE4A FB9ADB4D  
F330F08D F9E7BB35 BE4E782D 5F5DEAA4 15184240 3B26843E EE3C2B8F  
B2814E6F D9EA0088 6CB8E233 4E159D47 D8B77E4A DD315A21 3A828DAE  
526847E9 9C414BD9 BA9E3558 F11DB57B 9228BEBB 7560EEF4 50209260  
A3611C5C 347823D9 3B8280DE 242035AC 89C7FEAB 49123849 75CD41D5  
312B7FB3 C76CF446 989D32FF D2E23770 92D0920B 62BD8E4B 9593047C  
28667D81 A95043F1 09AE89D9 3ED6D676 63D5C337 BD41B176 2E5F1AA8  
6B2D4521 2C46731C 0420484A BB464C1C FD397C94 C791668D 715ADBCE  
AD488A4D ABC1FF2B 15188214 9B68613D F0ADA730 8C1C2F97 330FD4AE  
022110A7 E3197368 52AF0C64 FDFAB881 D19E7552 97A970A0 ECB899C9  
9BB30B9A 66D94951 F57CEE19 DD6229BB 1C195369 A48BABE6 0CD51B37  
8CDA53A7 4C5D5A74 1C244058 A888C0A0 6EE61DC2 CA0AC2B3 34B8F74C  
C3514EED A8E7614E E3265BBB 36B76C97 FE6A62C4 0A20E494 5AE7C9A2  
3F32D09D 05EA4A00 9F7CC2D7 CF083EFB D1FACCC7 77F5E29F 528DCA42  
0D4A5FB1 F3EEA9DD 436C6B17 21BF6901 3338FFD2 4921E433 6618595E  
3C85341A EEE90D14 F7752481 78785507 1BEEE94E 045D3584 E54434BD  
62D75796 0383148D F549233F 24CEE6B8 14722A28 BA377C9F FB0F212A  
F6EED10D C1E433A6 E04CB874 DCA5D93B B93AA536 FBBA8A10 9DDD3BFA  
B3C42EAB 4C4637E8 70E3430A DBAAC146 7FA39DA9 3416EFB7 C968CAEC  
BBF2BD68 6E8125CB E4DCB994 495A659B A3C4D705 2902FFEF 73AA11E3  
F2FD8CDF BEDD94E6 3CF14DC7 977F5632 00F74683 A15FAF81 3C95415C  
FF6D7A44 FD133E46 7B828F3D E9DEDD7A 6F8646F7 C16EF195 F6F16766  
B3272897 90821964 21CA7759 3340E37C 9E89F96B 779B22CE 4BB6DAA0  
94838285 AD0A82CF F5A2C042 6009E109 DA186D6F BE50FCC4 7C252209  
341E693F 66AC2B21 9CBBEFE9 9979E705 8689137E A66B36C1 C549AAF7  
E4294BCB 1EAE94C3 AA227A2F 5C3D1441 9D62C9DF 952C9E74 D7FB50CC  
35C59597 B59D7DA6 BE0120F3 640BEC53 BF5599A0 AC683DB9 BF33E3FC  
922B802F BB5F96EA DB85ECC6 73D4D9C7 A917BF3B FBEBBC20F 98A84F9F  
56A35D71 9E0EA3F0 98AF596D 5C0E6497 23E25663 4012E8C9 C1CA4DA5  
F9D0D574 888DD7E0 41803553 8E2F8CEB 23B618C9 DBFB80C 972C91DC

2C04F1F3 830CA090 25CFD16E 588351A3 1A04DBC9 6FFD2736 F699102F  
17D4D1A1 D4C38E9A 491BD133 D7BD3741 54131B2F A8E9FC12 A0ED10F9  
A35FF3CC D062484F 4142F2F4 5B73B7A6 202423DE 0EBAFD36 9779C68B  
4F52D6AF 5A21E233 A508149E E0473DE4 E6262DBC 11D9B13A 06865A5F  
A5E133A0 2FCF35F2 BC85B4C5 9C394592 4B323679 694F20D9 586BB08E  
5890D315 FBBA452C 40EB0529 7AEB3D4A C3CACE6A CBF8CDBC 810A272B  
61A6A370 5FB32798 354377CF 318494DD CB6C62FF 748BA102 2802EEC7  
D27DCBD2 BF89F843 EF6308A6 66B2BB74 E7420C2F C92D8821 4C5CD699  
B2C4A529 74808206 829BEAC9 BC1A1E95 F6E70AA3 11BAA033 B272E146  
34E5635E 0D7C554D 1EEFFE70 16EFDDDC 91D8CDB0 442B1BA1 A4CF619A  
4DFB28B7 FA433A00 1BD1C697 6A12E287 20E23F20 5D0F0DE8 4322C609  
B22CAF84 0A915D04 CD54E3EF BF78AFDE 5DDF7F8A 152C5368 04E7CC15  
B6EDF024 6D6D3049 E2D5192F EA00E0B3 32ACF7B3 35A429A7 F6080188  
D11B308D 9B9225F9 F405D79D A67C6869 A4264EDC DEE0EA32 7BA4A45A  
F4DCBDA9 39BB2159 42A46073 8BEC87AC 1865AFBA 2AC02966 13646311  
4F347464 1E7A651F 4C9B518A 06FDF256 52149EC5 7BF08A3D FE2E9485  
E3767180 EF516987 5B46E09A 389C37DD 6C69955A CAED3F52 22E777FD  
E7AF9C6E 16CD99AD F1B0A412 2577F8AC CAA6B071 111E3F7A CD79C7AE  
68816C78 6D6EFC68 F5087486 A59A8D56 9A90E7AA 459F1ABC F19BDD48  
4669442E 136FA4E1 0E501AC0 74B06658 1CD63098 E5A3D5C0 8671BBA2  
0789F997 4BC03698 8ACCF9DB D8BBF1C1 174E2385 65CF888E 4A4615E5  
389DB438 3A1C8058 E84A8DC5 9CC64E67 FF25FD2C E3693089 457008F2  
EC44A0B7 B01E6375 6860E5B4 6BAD510D 16CF4BAA 45F1ECC2 0082417E  
83EC7100 35EA1272 4C31872C 5FC905BE C1AFA59E 388AECE2 7BBA86F3  
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D296A439 98542A70 B4EB7451 7A48C19D ED48D9AA DF2112CD AB6E2418  
FC770B00 4F7BFBF7 5CB0EC5C DF4A96CD ADD784B2 F570AA4E A89EC31F  
7FB85B50 20502E73 8D83CF5E AC3D4A8E 1F00EB37 AD7C137E D1C515C0  
7414D130 A3E38C05 576E0A41 C822E097 333FE4B5 5846B298 EB648D9A  
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DC3A6769 8EBFF402 BB01A6F1 642AC919 9785FFC0 9C8FA99B 583A0A70  
13417434 17CB3F0F E4CAF114 26C2B770 4347819B 44718451 6BDE0569  
3EEC61C7 7ACC8FA2 8C601062 3E9A2C41 F395EDE7 478A8A80 E0F3ECD4  
91EFC6BF E3DAD79F 2A6245D3 5DB3E073 B23A36D6 951DB1C3 E30D83C2  
FE3AC978 F0B682D0 F72A55C7 FD6CBA75 22B27F59 D213D5E9 D5DF6808  
C473BFE4 E7F4B01B 0E75D4F1 0A44F362 9C50F1AB FF5E6D2B F8FB600D  
6C7F8222 D646921D 024179BB DE98863E 7743505E 45D1C4AF 6B52ED97  
A379BCCD 22D19BD6 11823196 DF7DAAD2 BDCADCCD DA750574 6483CD56  
CCB60118 90E485D5 F3482CD2 5897D973 490E3B5C 912C31F0 7D8093FF  
8A1E9EDF 18E6FF78 8A8CA096 AEB4F4BE 27B43767 7A23058D FE7F5AC6  
47B44D4B C3A35324 FB5B1028 9F6911F9 531BD0CD 98278997 93B647A5  
7BCBB7F9 32D88FBF E6073778 3FBA37B9 7C4E289D CE36B5A8 F2324819  
016B0A6C E91DB85F 26BB2D67 8AE2254B 18769DDE 158E90BB AB25A055  
327F0D7F 7326CE79 07F897BF 2C6FE1A6 79E03B89 334943C4 EF3334B3  
E5C3270B FBB9FBB3 7C5EAD90 0D3C7FA3 61543908 65A7C54D 1A17376F  
CC019B91 94C46BB8 DF13B466 19F970DA 48B7DC74 BAAE412F F93C8432

C34AE108 0D549DAD 2EB70BBB 60E48552 1A2541EF A6891DBC 6402D1CB  
1B7C192A 5FBB4CB7 D34EB830 ACF707FE 5BCCD1FA 915AA561 80757555  
B7A3CFB2 A0A5DC16 2C19D9A0 1BA1AEA8 DDDFED09 DFECBB7 9F05A45A  
CC5F5A64 F0F70590 9D16B72A BEE727F0 D25F8675 155AC2E0 DE3AAEA0  
83A860CC FA6312F6 88A5C6B9 0F6BAA8D 542D3810 E25D5355 7A566A30  
D08DB9B0 918BDCD0 6EF73B3D 40DD1B0C 405FB324 BCBF9A3E 865B0BD5  
4CAD2CF0 B12D9900 356CC65F FD5D2A5D 5773F233 235FCC6A 18835407  
AFD2E2AB 46C25653 CC59CF8B 29BAD15F 5DBCC294 BD319B9A 4FDAD597  
203EEC6E 7A78BDDA D94EB457 BDE39E7F 973FFC58 B5E41657 3A974478  
D9F76402 BB888A83 293AFF15 6B0AE2FB CD212F23 0CE4F020 A78E89C0  
FA7A79A0 033DD06F C6792668 4E59BEE7 3C4517AA 8B70AEB4 C5C2A5CE  
5AEB63BD 2324D51C 41D4D072 DE69C213 43AA2A2A 9A6E49D6 29123D94  
84F870F7 F545F702 45C0D7DF A0DB1448 56CFB7F8 5157788E 2088A620  
07D7FFDE 39EF97BB 351B168F 3C5A9815 E03F80FE 2CB444C4 CDF93F38  
79610DA4 F618E931 077C11E3 559BEDD0 3673010F 4BFFD9A0 A271282B  
54BCD69C 33961AB8 0F99AEDF C8574FA1 04937833 53947E68 7C3BF500  
DE1C2F0D 6AFCF913 55876125 DC76669D AD688442 C81BD2BB BFCE55E6  
6BC66DD1 99DCDB53 D98DC931 48C107EA 9188996F 19B3D6D5 F48011C0  
69BA18BA DD824FF9 C1090260 23296CE0 A99CA0B2 F7BFA276 5FCA1443  
DB988BB7 8243E968 1399E840 590CF0DB 712D20F8 15E55273 98248645  
545F5975 821D9082 48F3D991 7676ACCC 041A0E5F 38072C85 D57C284A  
09B72812 98EE094E A1865926 886EFC84 C2B0156B 41D17082 E6BA61E4  
D0F836E4 F5FB4153 AADA3862 40B62710 65B90DE0 C823165F 4EFF12EB  
C0748878 D944EBA7 56766B6C 1B5E6375 BD2A0BD3 72A700BF 2D73F653  
2DD48D74 80ABCE66 18CCDE47 469DD21F F09BA448 B03EAEF0 171FA440  
AC3C10F5 3C6E1D0B 05B2EDD3 55951391 33DEA6C6 69ACC262 AF421A05  
20784221 CF2F2430 D415CD7F 2C2B5E62 64C018AD 37E11179 08AC97E8  
BD0C2024 E5EFDEE0 21606DA2 D3E01E11 DA2BCD9F C58BC76E 9340F27E  
5496D62D 21C8E3F9 D772A350 E55BBBD6 A1AC33B1 8ACF0F74 299911DA  
76433F5D B0896E8C 0D586AEB 3D073A05 7F6B21F8 39130267 7B988C08  
71FEA48C BBAC8FA0 668F2581 4014075B DE16C33B 594958B9 F7FE917F  
777E9EE6 7ABFC7F6 7EB6726C 88D494FE F1B8B7CB 4C9E7F24 8F477936  
3E5E766E A85040FA F21E3B4C BCF4B713 97945EF0 BABFCCAC 4D055DA0  
54143119 3AF46B18 AD61B929 BE970F8F 34E9C365 BB1A719B 53D5295A  
DF294847 96FCC450 E581516E FC9618B9 9534D28D E43867C4 B34C2F46  
DC2828F5 83FA3748 2E5BBB08 FEAC1F46 B14DD9B5 F860A543 5532AFD1  
CCEA717B 76D75784 095FD77B A160E339 7AFBA079 6414EC32 53E7EF40  
9FB67387 7FEE7CBA 47B94462 5F2C8FCA 1E46793D 13007163 E7254E3A  
7FDB332A F00BDD17 DBC4305C 76EBB1DB E436A1D0 9D3E0A8E FAEEF2A5  
2A530438 AC3D897A 52508471 0676E847 449612A1 2102BD6B C5DE7308  
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189BD1A3 3252C9EE 71A7123C 38A7E950 E5EDB15E FC3A7052 2DE21B44  
9207DD2A B5618C90 1E79FF1A 39719ED2 2BD0FDD8 B126176B 11D28EA6  
8CB7114A 6C9647A3 5D385605 D6A7F866 10803880 A8317B1E 6F6212B2  
4E3EED03 9D11D42C 33FF4E2A 6EE36127 D35ED2BF 13DC2871 C2ED51F2  
8D8EB885 E0811825 61E36D9A B908BE82 931C89A8 28F400FF C64DB7E5  
7EC47931 C05E2099 A71B99E3 4BA6B834 20031E9A 1AEAEC6 F223F08F  
9EFC91AF F8242A97 5B475191 19FF6A0E B8F97DC6 EFA5BC06 DA0ACD6A

0472CD79 648ACA91 7D3792DE 2AEF08DE 33546BA3 97916102 011472E4  
05C4FC23 7A3C5755 FD9F7B99 5F13280D FDBA02AC B07C1F56 60E914DD  
82BEB2D1 D1F4AA2A 39DAE80E 9CD83BB4 D9D75201 3DAD14A6 32EAB8FF  
4C4B3C75 EF10C366 BD220C53 09CBB530 473036D0 8C9132CD 681365A3  
CF504226 06E6A470 3355555E 1A534F20 3CD84E8A B695E0F2 4ECCE754  
19EA9804 9C79CCA5 841FD95D 40F8AF44 26637318 65886EF8 B6F306EC  
AEA990A0 A605ADF8 CBB7D4B4 3C845601 A8E6DDAF 22AB2430 248FF24B  
6FD06D61 EAE1950A F970D01C 1C368E70 C78357DD F6F4163E D3F6FC97  
E58445C5 0828F650 DEA74894 A2F22764 603980AC EF1858CA D6A2671A  
112DB70A 99F0859F 211077EB 0CFEEA31 A20EBF06 FD33DC5E 4C0585DB  
C496B177 137CC30A 9A7AC5C5 7A250A74 6FE40F75 BBE2EDF9 7675F792  
C1298166 952AC141 5CFAFCFA ACB9F0DE 3DA0433A 717A79D0 49063787  
7B04D725 B27F8742 9CA9E3EB 9FD4D0C9 CD39FDB3 979E7EEC FA5F8FCD  
D244F3D5 E0C17D97 76C8E7D7 77B4ECA5 585D9173 50FED8DE F808F4D5  
A4B75978 93784DA7 D7448AC8 1083A7BD C7D12795 F3EF735B 666FB18D  
A3AEEA73 1F7ECBC2 9672B11C 08EE8F05 36D3ED19 383F95FB C967701F  
E3836D50 BF5CA299 C912A831 754FA7C5 AB5862CB 3D56AD0A 3FDB1D36  
2E74EF21 279BA17E 1893B4CB 0BE77E07 36DDF543 B3A9B645 FE54182A  
D699A60F 1BFA6C7B 558B73F4 512254D0 07DC8523 F19D8588 95CD1D85  
F65588F8 E957A020 1854BB35 DFCBF5CE 35D2B12D 834D6FF0 4EB3898B  
BE4423AA 73C05FD9 94F6F686 6F6EAC93 B3CBE4BE 5184CBB7 7CBCCE43  
2D19F398 BB9E131D 5B413416 EE0BEC76 4B5D1C12 55E73971 E1407029  
C5B79F7A 1DF7F568 C677A708 B79076A7 4F0EE2D1 D9B41E72 1343FFE2  
1FB3A194 8C42950F F7D54249 5D008BE5 EA218BE8 6282F771 167649AB  
8863D8E9 C79BCF9D 68E56D70 CD9F9195 6F42E0E3 22F83AE9 9958C4F5  
F0BCB0CA 88510ABD A8001D73 2E38D608 E0699376 AA8CE93D A13E35F1  
7958F787 BA234459 2B908A21 0926E109 05ED7625 131B8B54 22CDD1DD  
694267BF 4CCE00AB 160C323A C00D7FF7 9EBC9896 301FCD8E C327892A  
CF1AC575 3041E0B0 8F0D45EB E0514DB1 B8C413BE 6939600F A7DAF9C6  
CA366CEE A7052B12 0403EF97 C232036C 5B481347 28600824 91C73293  
476A6465 71BE2ABB 45090323 7D479288 9B171949 BC06E34C DB8D9415  
7AF13FEF 717D16F6 1107BB7C EF7AB81D 87808FD6 893A767B 9FFBE55A  
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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

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