

FIDO2-PQC: Proposed Implementation of Passwordless Authentication with Post Quantum Cryptography

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Abstract:

FIPS-204 has standardized Module Lattice Based Digital Signature Standard (ML-DSA) which is believed to be secure, even against adversaries in possession of a large-scale quantum computer.

It is to be noted that with the recent wide adoption of phishing resistant passwordless authentication standard like Security Keys, Passkeys and device attestation following the FIDO2 specifications, the adopted cryptographic standards for authentications have been primarily ES256 (Elliptic Curve Digital Signature Algorithm with SHA-256 on P-256 curve) and RS256 (RSA with SHA-256). Though most authenticators support other algorithms as well, the default algorithms are ES256 and RS256 when anything else is not mentioned explicitly. It is also be considered that neither of these algorithms can be deemed secure against adversaries with large-scale quantum computers.

This study proposes an implementation of ML-DSA for passwordless authentication with standard FIDO2 specifications like CTAP2 (Client to Authenticator Protocol v2) and WebAuthn (Web Authentication).

Introduction:

This proposed standard describes how to use ML-DSA keys and signatures as described in FIPS-204 for Passwordless Authentication with WebAuthn and CTAP2.

Algorithms:

This standard proposes the use of ML-DSA-44 and ML-DSA-65 in accordance with FIPS-204. It assumes the COSE values as represented in Table 1, which has been requested by IETF for IANA COSE assignment.

Table 1: COSE Values for algorithms

Name	Value
ML-DSA-44	-48
ML-DSA-65	-49

Secret keys:

FIPS-204 defines 2 expressions for private keys: a seed, and a private key that has been expanded from the seed. In this document, the authenticators are recommended to store the seed considering limited storage in HSMs, TPMs and SEs. The ML-DSA.KeyGen_internal(ξ) function as defined in FIPS-204 can be used to re-generate the signing key and verifying keys from this seed.

Key generation (Make credential):

Web Authentication defines the credential creation API. This takes a publicKey object which is of type PublicKeyCredentialCreationOptions

```
publicKey: {
  challenge: h'.....',
  rp: {
    id: "example.com",
    name: "example"
  },
  user: {
    id: h'.....',
    name: "johndoe",
    displayName: "John Doe"
  },
  pubKeyCredParams: [
    {type: "public-key", alg:-7},
    {type: "public-key", alg:-48},
    {type: "public-key", alg:-49}
  ]
}
```

The web browser or the client operating system is responsible for communicating with the Authenticator over a chosen mode of transport (as defined in the CTAP protocol) and send a CBOR encoded command to the Authenticator.

The CBOR Command for AuthenticatorMakeCredential function under the Authenticator API in CTAP is 0x01 and the payload is supposed to contain the publicKey data in CBOR encoded format.

The payload for the CBOR command can be represented as

```
{
```

```

1: h'.....' //clientDataHash
2: {'id': 'localhost', 'name': 'Demo server'}, //rp
3: {'id': h'.....', 'name': 'a_user', 'displayName': 'A. User'}, //user
4: [{'alg': -48, 'type': 'public-key'}], //pubKeyCredParams
7: {'uv': True} //options
}

```

The same when encoded into CBOR string, can be represented as

```

A50158201637B26333915747DBDC6C630C0165405A64939AE8F6E4FC39414F853F702F160
2A2626964696C6F63616C686F7374646E616D656B44656D6F2073657276657203A3626964
504EC1D4219F294FB4A0BC0CD29D485AFC646E616D6566615F757365726B646973706C617
94E616D6567412E20557365720481A263616C67382F64747970656A7075626C69632D6B65
7907A1627576F5

```

The authenticator should use ML-DSA-65 (-49), ML-DSA-44 (-48), ES256 (-7), RS256 (-257) in this order of preference if it is available in the Public Key Credential Parameters. Other behaviors of the authenticator to be used should be following the Web Authentication specifications.

When the authenticator receives the AuthenticatorMakeCredential request, it performs the steps as defined in the CTAP Specifications. It generates a keypair. The private key is to be stored in secure storage. Resident Key requirements should be followed according to the Web Authentication and CTAP specifications. The public key or verifying key will be COSE Encoded in the way defined in ML-DSA for JOSE and COSE Draft by IETF.

COSE Key for ML-DSA-44 would look like:

```

{
  1: 7,
  3: -48,
  -1: h'.....'
}

```

It is then CBOR encoded. A CBOR encoded COSE Key for ML-DSA-44 looks like

```

A3010703382F205905200BE1BC2EE2929614D3046FA3FE8A4B486E06ED3785CDADB376C9
DA86562838FBAC8D1B58389806367BEB1BC562A976A60ADE12D71E377EF4F9AC17CE1C2A
5AF85F8F550269B5467A12BFCA1C361EA85DDD339760430ADB49A12A1702AB7F77453641
1FC4B1E9AA4D91E038B4290905D42522F5B7CC2B8B3015976852B39973874B2D3FD81918
F053D413EFC4DC8852BB427AC16B1D9EFA8E0CB883B555CE94356882C0A0CEF3100CEFBF0
127C08765B669E6A4CFDB297D667EB123629F136F7D34BCD017003CB4C0141BA21B6F77D

```

05C8FBDF749D592094B7DAD742902FF76BCFCB1C284C3970F82135227DA7798C764BA354
27DF01B43B26430E831390088E5993E273266BD168090F2B4F0582DDEE916C9036F7F5C54
5706D8C3B527E1729BB76BC6000543D22C9DF56C6F47B041770AA95C2E1BFB9B091F9C4E
B0BA419886F65E4888119551C1FFF3120BB430C3012AE3DF6C591D81D146C611DB70F3979
AE99F0E43939A611085D83783164F5D77982FEF8988F5118CF064A886931D0C2756821464
8E72CF1A5995B85A531B576F0EBE1096A460705F55C6F9A2D44BBFFA519ED0C4D9DE0BBB
6D09CAD230FACFA6BE88B4E929E9DC92A5BFCC349FBF4E182DF5508C98481CD293BD9296
45C5DC15FEBB46E66A05B123241BD3F5CD2FB17FB5008BC2BF8236D73323F1DA506AA578
9620912CF9853FA82C8B6CED2A5B2F565EF17B39F5679DF7D552A7AF5A2F8CD46B18FA685
5217AA6ADB5DBE8F45B73BAD10BEA4A26D948168795FCC2B74F3DEDCC8EE1BFEC73EB56
588917AAFE09BF511C2C0BC32E901F33C0CC4DD0224FB4E4EBDA780AD11E9B184EC480A
B0377E8549078E393BA4AB9032F14081B3E6BB50B998D1F89641EC3F565BA8AD3BC5A3D9
635007FAC2879E2379820C9EE1E3DA760A555BA3B6A55138AD55F67FA9869BF26E50263D9
0AB58B4E1F61924BF6D3EF18759BBAC28281DA54B6F43BDFAFAB6811C0CB0F074B37254D
142615CA5D4021BB40075156EC2421B86ECC7A2BC2F1BDD078E893E35F44131277EE1CBF9
7F7EC4E00493ED23E32824F079A30F9808A87D8D79A5958654618E986B4983E7BF9E269A7
C48FB98C255A1CA4672C7F77E685118860EAF3423A00D7080B1053C30D7B804861004AFC5
3EEB98E63114AB5B9D77F22E3796A405D06B265DB7DC51C8C202655E1314A2174E3EECF1
5C0579DBC97BF8D2B1FC4B264E92A5A20C4AEF7291F983CB7605FE8A01F7413F5701E5166
EA863FC85BE9C1CFD880520A1B1E144AA9DCC3668275FF973F4F15634BB5D92F3EE407A6E
32CF717A925B9D4B9A9FA13D12DB088E6C53DDE00588885F1761938EB08C57F99CF85522
72B3554F557FA7BCEBC48144AB539A9E34063C3BD8DE9D59477B8574306FAA12834FEBBC
9BE00010A8138338B5061800AC7A682208EAC2713FDE393A9BBFE2996012EB4B8C064801E
7DFD0DDACE34D69BEA0E641BC7D8BD6C37BD12CF28BDF1394E149348BD0D90C66590697
2252836C3E9F90DD15A969E3678FC8A2E654BB1BDA9EE735FD6B2501A6C907ADF5137017
7A907C85C423F510CD1CBB4275154970FA6A7EDE91C9CEEAC63F3879D0FB8C92DB457D99
15C645539AA55216E215D861BD8A02703C63F8941EF966CE730525FB6B70A02709AE6296
A11CB74B937BEDBE20A7A28431F81FF0A0FF6166311C2F5764AE73B69EBB4944CE5498979
124393713CAC2247FC1DDFCB9ADB965CDA54E9618E2326771D46FAD88EEB6B534C4D4303
1CFFA876ED74882278342774495A5BD48A132154B48038A168BAA8A619A6D78D8960FE3A
89978FA4C0AE4498F93451F6C07189BCD5EAF8F04

To generate the attestation statement, the following is performed:

1. The RP ID is Hashed with SHA-256. This will be known as RP ID Hash
2. The credential (keypair) and credential ID is generated
3. AttestedCredemtilData is generated by
aaguid+credentialIdLength+credentialId+credentialPublicKey (where
credentialPublicKey is the COSE encoded public key.)
4. authData is generated as rpidhash+flags+signCount+attestedCredendialData (flags
and sign count are defined in Web Authentication specifications)

5. authData and clientDataHash is concatenated and is signed with the private key. This is known as signature
6. Attestation statement is generated following the attestation statement format. An example for the same is {'alg': -48, 'sig': h'.....'}

The attestation object is generated as:

```
{
  1: 'packed', //Attestation Format
  2: h'.....', // Authenticator Data RP ID Hash (32 Bytes) + Flags (1 Byte) + Sign Count (4
Bytes) + attestedCredentialData => AAGUID (16 bytes) + credential ID Length (2 bytes) +
credential ID + credential Public Key (COSE Encoded)
  3: {
    'alg': -48,
    'sig': h'.....' //Signature
  } //Attestation statement
}
```

The attestation object is returned in CBOR encoded format, completing the authenticatorMakeCredential request.

Authentication (Get Assertion)

Web Authentication defines the credential request API. This takes a publicKey object which is of type PublicKeyCredentialRequestOptions

```
publicKey: {
  allowCredentials: [{id: h'.....', type: 'public-key'}, .....]
  challenge: h'.....',
  rpId: "example.com",
}
```

The web browser or the client operating system is responsible for communicating with the Authenticator over a chosen mode of transport (as defined in the CTAP protocol) and send a CBOR encoded command to the Authenticator.

The CBOR Command for AuthenticatorGetAssertion function under the Authenticator API in CTAP is 0x02 and the payload is supposed to contain the publicKey data in CBOR encoded format.

The payload for the CBOR command can be represented as

```
{
  1: 'example.com', //rpId
```

```
2: h'.....' //clientDataHash
}
```

When the authenticator receives the `authenticatorGetAssertion` command it performs the steps as defined in the CTAP Specifications. The private key(s) is/are fetched from the secure storage. The credential ID of this key(s) is/are denoted as `credId`. Resident Key requirements should be followed according to the Web Authentication and CTAP specifications.

The following steps are followed to generate the assertion:

1. The RP ID is hashed with SHA-256. This is known as `rpIdHash`
2. `authData` is generated as `rpIdHash+flags+signCount` (flags and sign count are defined in Web Authentication specifications)
3. `authData` and `clientDataHash` is concatenated and is signed with the private key. This is known as signature.
4. The credential descriptor is generated in the format `{'id': b'.....', 'type': 'public-key'}`, where the id is the `credId`
5. The user Entity associated with the key is retrieved from storage. It is of the format `{'id': h'.....', 'name': 'a_user', 'displayName': 'A. User'}`,

The assertion object is generated as

```
{
  1: {
    'id': h'.....', //credId
    'type': 'public-key'
  }, //Credential descriptor
  2: h'.....', //authData
  3: h'.....', //signature
  4: {
    'id': h'.....', //User id
    'name': 'a_user', //User name
    'displayName': 'A. User' //User display name
  }, //User entity descriptor
  5: 1 //numberOfCredentials
}
```

The `numberOfCredentials` field as shown here is optional and is generated according to the CTAP specifications for Resident keys.

The attestation object is returned in CBOR encoded format, completing the `authenticatorGetAssertion` request.

Experimental Setup and Performance Analysis

The Open Quantum Safe (OQS) implementation of ML-DSA algorithms have been used in a quad-core ARM Cortex-A76 processor-based microcontroller (Raspberry Pi 5). The microcontroller has been configured to be able to communicate over USB HID and a custom implementation of CTAP-HID has been used. The custom security key is able to work with ES256, ML-DSA-44 and ML-DSA-65 algorithms. A few credential creations and authentication have been attempted to benchmark the time taken for the process. Table 2 shows the time taken for the same.

Table 2: Average time taken for each function

Function	Algorithm	Average time (μ s / microseconds)
authentication	ES-256	3192.7
authentication	ML-DSA-44	17800.6
authentication	ML-DSA-65	30675.2
registration	ES-256	12251.8
registration	ML-DSA-44	36069.2
registration	ML-DSA-65	68086.8

References:

- FIPS-204 <https://doi.org/10.6028/NIST.FIPS.204>
- WebAuthn <https://www.w3.org/TR/webauthn-2/>
- CTAP2 <https://fidoalliance.org/specs/fido-v2.0-id-20180227/fido-client-to-authenticator-protocol-v2.0-id-20180227.html>
- OQS <https://openquantumsafe.org/>
- ML-DSA for JOSE and COSE draft by IETF <https://www.ietf.org/archive/id/draft-ietf-cose-dilithium-05.html>
- IANA COSE <https://www.iana.org/assignments/cose/cose.xhtml>
- Yubico/Python-FIDO2 <https://github.com/Yubico/python-fido2>
- RPi Security Key <https://github.com/AdityaMitra5102/RPi-FIDO2-Security-Key>
- RPi PQC Security Key <https://github.com/AdityaMitra5102/RPi-FIDO2-PQC-Security-Key>
- PQC FIDO2 RP Server <https://github.com/AdityaMitra5102/python-fido2-PQC>

Appendix 1: Time taken for the operation multiple times

Table 3 shows the time taken for performing the operations multiple times.

function	algo	Time μs
registration	ES-256	37810
registration	ES-256	5601
registration	ES-256	5898
registration	ES-256	5871
registration	ES-256	6079
authentication	ES-256	3435
authentication	ES-256	3132
authentication	ES-256	3295
authentication	ES-256	3089
authentication	ES-256	3184
authentication	ES-256	3080
authentication	ES-256	3377
authentication	ES-256	3051
authentication	ES-256	3201
authentication	ES-256	3083
registration	ML-DSA-65	68796
registration	ML-DSA-65	67511
registration	ML-DSA-65	70420
registration	ML-DSA-65	64257
registration	ML-DSA-65	69450
authentication	ML-DSA-65	30142
authentication	ML-DSA-65	31431
authentication	ML-DSA-65	30696
authentication	ML-DSA-65	33001
authentication	ML-DSA-65	29139
authentication	ML-DSA-65	32220
authentication	ML-DSA-65	30723
authentication	ML-DSA-65	31537
authentication	ML-DSA-65	25272
authentication	ML-DSA-65	32591
registration	ML-DSA-44	36482
registration	ML-DSA-44	36288
registration	ML-DSA-44	36220
registration	ML-DSA-44	36003
registration	ML-DSA-44	35353
authentication	ML-DSA-44	16908
authentication	ML-DSA-44	18794

authentication	ML-DSA-44	17441
authentication	ML-DSA-44	18481
authentication	ML-DSA-44	17583
authentication	ML-DSA-44	18340
authentication	ML-DSA-44	17716
authentication	ML-DSA-44	18794
authentication	ML-DSA-44	16055
authentication	ML-DSA-44	17894

Appendix 2: Sample CBOR Inputs and outputs

It is to be noted that in the following CBOR examples, the first byte is NOT a part of the CBOR payload. In the input statements, the first byte is the CBOR command (0x01 for authenticatorCreateCredential and 0x02 for authenticatorGetAssertion). Similarly for the outputs, the first byte is 0x00 which signifies the execution was successful.

Credential Creation ES-256

Input:

```
01a5015820afedb91cf6971cecb8f26d2e066cb1333efa942420c254bc30235e5ce12eaa8a02a
2626964696c6f63616c686f7374646e616d656b44656d6f2073657276657203a3626964505bf
7dbad54524776be382d2376293742646e616d6566615f757365726b646973706c61794e616
d6567412e20557365720481a263616c672664747970656a7075626c69632d6b657907a1627
576f5
```

Output:

```
00a301667061636b656402589d49960de5880e8c687434170f6476605b8fe4aeb9a28632c79
95cf3ba831d976345000000044d41190c7beb4a8018adf265a6352d0019f785d850be6b4bd7
b241c30f69efd61f5f6372797074616e65a5010203262001215820a58e44e07b296acfe39088
46c7230b8887c790a19c0d75bb31d51b7a26dd1f225820225716514d192d4c5ba6496e2a66f
b93e5afdf02118371099917423e88194a7103a263616c266373696758463044022045ecc72d
c3103ec407e6a6e1cd40d9c11d69d12dd1df7ef2ef8a9e71d943de0902202bcf5b7c6f8c26207
64d3a9f31e4711d55358e77187abd021a366a974fc41e
```

Credential Creation ML-DSA-44

Input:

```
01a5015820da8361bcb104b3e7cd4681cf80b6a96a2c788222b4b8218ef5311182c2ad7f0c02
a2626964696c6f63616c686f7374646e616d656b44656d6f2073657276657203a3626964504
7787fd9fa0b4b6793cf7a75c388f919646e616d6566615f757365726b646973706c61794e616
```

d6567412e20557365720481a263616c67382f64747970656a7075626c69632d6b657907a1627576f5

Output:

00a301667061636b65640259057a49960de5880e8c687434170f6476605b8fe4aeb9a28632c7995cf3ba831d97634500000044d41190c7beb848018adf265a6352d001997e93509765f4a088d9f6a8d7f9314c55f6372797074616e65a3010703382f20590520bb2f031ef8a16176f0079737d9f5df04ea7b8954a899086212a8b859bb3cb1e38fa241a3a7dc90f25b2492031c1aea0f3ee3b91acdc167110dc68cc16d192a6d847f1149208bed109d9eb4b2d73343eb3ccb73f711c4cade91fc158e501cad07fe1d2730600e3615b2689b074662ac60b6964edaf20723cb2c43492415fc3931db0881e81fcedded9ba9140ac0ddb7e11ac748f003ff309fa0a4d845a3e56a9c786bd35e91b2c6ff62d6dfc50ec9719770d15c98578727cb99371e34f112615e2198d7820ca64bde86196ea352fe63a047e8d0b0a1a1810c368eab063f0e4115db8bf08b4abfb36cb87cc8577b7a44b0c65dc12fd17ce44ccc29b469ba45704cc4de8fa293f975ab1278850accbc70c7773d1e0995b876c3fc924b00b4357167544ffe712b66eebf6562d86a4585d43a8ba8c2e1564906d6a38fde232a658d5a7aea2f9871c40f1d5ebbbdef5839478c029711bdd3c4e954c0c68c013361f5c29d373572c0e4cc770c4e996b7d39ac42eeb82cd28b056bfb337d60e89066a5e1d0faf04f274bb92465fc092e6efdb0026866cf9844f9bd7f3574204d9c90ceb3ad8f7b91d87179d2c8c096da05dd1d8a04760d7fafa56dc51a0c3d5b0b1b8c2deb5222a64da7f4fe5e1718d53b9901a24973bee90dc216d9065372b63eaa71ca611887752ccf9e2a2c0a2363d4145779caa61cbd0fcb963880396c25f15c109f9e246eb70e06b69605c488b92d312d70069037384d4e62c456ab4a54eae313e6efa3bd98f8a9914ad347c2dbe788ecfb3d73ab299ba593c563f9603d06719478ad1c6204ba88939378440a9dfef93bee6943626ca029c5143e66274f22ee9e251bb26b76193bfb604666043af8c709943563cc2558b75eccf5ce5d19e0a2b1a17713057bac1a3d39246d625ac74647180df31077537e0b5e40d1a4a270be6b7957da27562ea5d4918d3d86a717394d1c81ab5d34185e9ae22798046076763961896e842febc7fa718deffeee0e134d12a19ac5370fd09f4e5337e1175ee7528ce4ba6d97a030d02b25fbddde35df2e2af84fe6a9712b30c942c5818829e49085f5c2747b192a698f05d35eb21835eb6a6dc47cf2228423ec5051da5bf411f42327f3b09632ae19a062d394b7f73bc428068dc73195da660da1ed09a78fb10650142c127f6d24196d1ce6bcb7fe40a916557a48005ade487419e5d42c2f6bd7903cf7bdd6ee6b01a7f92da64b6328e65eb18d111e1a8c3ba1141c9ab8a181f7fd56561cc550e760ce682bc3ab97530194d5dfd9c990abc8671bd06785b334e55f82e369946e8b403f10642d93108365ccf471116230395c755bcfe2dbbb65a806543c00ed0c76376476ff10d9d2457710c253896688c4a4afca066e8064a91b3d465307e6bbd884f0bbb02daaed85b78065e382b9fbd16d8fc894eb453ee821b8b536d7e544950f86eb902e8e4ecbe12cfd4f3b05d22334b8f6b3837b61d7d1150243deb0ebb78dc4746690240a1427cb9af265c32c0c8b073b500857bd251dbcef13b6a2f34f6769d6d94e2c11db8bcaa9482dc5d4442a916f0c2ddb00f767817d9210b3fd3138d300e80b595dc2caba7c43eba93ed75790e3b06e25c352cce763f2c92de272e6fb0112d5d052dc59d7a8693a1ce5e93adf4d89930adf57d77055e667c6780fdf52083aa9370dd643a953fb36b31c844e19168ca3d681102069fd7398736cfa75d80d03b51fc4cfe11e3c2cc0943f7791bf1040f3349ef573ccc85f12ce66da0b981739da7ee4961287fd5639df851e2ac73419f8fb4c4928cbac1c64b2a349731c9c703a263616c67382f63736967590974

abc185658345af3ffb48f88450ee5ab012f705e7bf1d0da3bb31e7b536e31f269526dfbc09654
b02931ff6c7d2e295fe9019181ac39b8d01b864efa8837cebb6836e90569b684845cac715c1ff
29507eb0de608c2e08d43007e8ca09acfa1094df1b055267d72652d8928983aa25872aafd600
2dcbdfa849a0351344e752fbe7c10cc87bb679c25841bc4c981ba743e9d4583fed3007bc4e21
90a5632dfc243dff68a1d9a57390cd83865cd4b7a018e878c9bc2db1216eeb81fc7393c8c5d0f
76818a250ca69869498f331c44c16d4af32faef5993aab6d4061e1b169b6cf8202232d76bdc3d
a3e5265d763648f01a23f237205b609698c09926467ca8681b9b120d94fa437bc412433eba16
8b122aaacf246d9d58736a08a8acea668c94821a9476b3ff4b53a508b286e27756063e84adb6
2a85bb9c423e1c13b3f12b9e1fd533de58f2ed39668a5d82f86554135b6d1fb6ba0d14e704d7
5a8be090cc4f29d6bee2ee8090c659cec6a56a5a3ecc877e41230b210bd679bf2949d0855d51
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Credential Creation ML-DSA-65

Input:

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Output:

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7252f647d3cd2d1a72fc854636cf96ef26ade808a212c27fe22234c3f93bef6f8e341f5828d0cc2
0afa58168eebcff5b0e04323147d521e574079714c5225992166ba61f1054de1d4899606b5e2
111a85ea106fdfe7776032db4d42d9cf75c8a421820b1f03290c951014677743c1bef216fdc15
de342f9d23d8fcb078105da4ac211329365c3f264a8377d2ee8377d80dc486480faf24956a15e
36841cca151b0442c0801e2b8ee258c6c7a3f968c7bd87d4599da3d5b8f9bcc3d02be135e996
ae012af494f0509887655c4fef7ccca5cfa77df92c4bf2a2679d502580e9e1371ea82c38fe3fee2
81486600cafa4c10ffb1074e08b91c038eb4edcdf50715c0d9b5c9db421293408e80e54b4ca6
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06d9e72ce14d54eb6f0e71bffc683aaec24d56b6cba4d1fda0b61383ed6a8796edd05a0798b
b9101c9a51284d8cbc2a993ac88f9e7ba20808acefbd0a17114818400f4cad2308a3170f16e57
7abdfcef3564cbafee1f9475e9c023acc3a2d40c446b0ccd1e563a701191d33fbb122c8b284fc0
9275686314f110ede3f76bedbb3649363d221ac16e2e8ed79d5a3693962743be5059b451e39
76b8a6d58ee9b3257a2cc4275db420dc6c33bc22d9506da94cbd08285a85be7982bb477bd9
5b640520f2dbe7118b19d9483407b055ad82955448f50021b16f7aa8ec7d1349ca29bc465c1
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2f38a63330605a6c40c5ff3bf68a6da1517fb95c64e02f98d59494406ba8491b1774d3b9af147
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31ee2dec75027dd22c19166a0358eebd7bbd40d5a86e5705c0a1e59fba34ce37476e5fc9ae2
93b5ffc42e61d1d2710092609cf50e4612e194e4db5320af9587b3a0dca4b88a892784a56f21
748d76be226fe38eaddade367f75b6d45caefd2dd797edbe69d319f52e9ab2b47a7ade1e8f00
71a5052193a456f8c9cab4d2fa005960851041797e99abb224353e6f809abed800000000000
0000000000000000000070b15192028

Get Assertion ES-256

Input:

02a401696c6f63616c686f7374025820262ae1aecf82e3fd33489a3a70a59d2a0db161e6a144
eef412518fe1fe3bd4460381a2626964581911402ef9ec5f449eb8ea1d5f645a0e585f6372797
074616e6564747970656a7075626c69632d6b657905a1627570f4

Output:

00a501a2626964581911402ef9ec5f449eb8ea1d5f645a0e585f6372797074616e6564747970
656a7075626c69632d6b657902582549960de50e8c687434170f6476605b8fe4aeb9a28632c
7995cf3ba831d976305000000040358473045022100aad84e3fddd28d95223a4c33f9424578
8f99f2bbfdd94c700109ffd336f2b6022062a8f2dab99c1945cfb03cab0a77fa8e4f591389aebfb
caae22d4af126f6d1c304a36269645065fd82a31143f78f40697a0938af90646e616d6566615f
757365726b646973706c61794e616d6567412e20557365720501

Get Assertion ML-DSA-44

Input:

02a401696c6f63616c686f7374025820b74ec47517bedcdf7b73a68a7b03ad5fbbdf1c6ce9507
05a0e7d49fcc998f76b0381a262696458192467a4d62c03439fa0441e4d829cf7cc5f63727970
74616e6564747970656a7075626c69632d6b657905a1627570f4

Output:

00a501a262696458192467a4d62c03439fa0441e4d829cf7cc5f6372797074616e6564747970
656a7075626c69632d6b657902582549960de50e8c687434170f6476605b8fe4aeb9a28632c
7995cf3ba831d9763050000000403590974617dcce5f68e669552b905fcaee91a42a1b5cbf45
128cc740f03189cb4a376e39f7c7a855a6bdadcc2ec3a7c5ecdab897acbfdd6d7aa623ed871c3
9da9ff4a62bf8307f764472560fac2e3871de88acb8e9d24ad6216c9cea70249271c6f53a73da
e85b76c5147872dc17455f9523f8d74f704d0d17bc329de220ab6c9668b6b0de122a0fd6386e
5bb9e5831fa9e018d78423763f2080e23796f4bce11fc843999d4cea7f9d038948532a78386a
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43c836b70c347958e4f445df1cf8854fb99ba7ffa2ca5fcdd2e455c18a557e899c51eab7be93ac

9cb5774512bfd15512e54a5b175e466fa4f01a7ae3e0b6c7cc4aa7696c4289b575f89229b3cb3
d4b73acbc4995fdfd3fbcd3b99d8230286e5bc02e4c970feb67533cec688bc83cf907ce49ebbb
96e9a14c7e7f39d0f4243b8f7006e486d79fb38a105e3bce6cac0dde583b8df9e0bec1a64a397
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8ce5ab7dd451bd2b069d4a74998e49aa3303f579dfc497a48f4e5df660638bb427b320975bed
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6548fe8496c41e62e5db59925deef2740b5e91ec6e4f185a036eafc20ec49bd43f942608266ab
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f6f6f67aa5e389b701ee612c8ab4397430c267a58e0c6c56f89a55d36e039124ee669a541762
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Get Assertion ML-DSA-65

00a501a26269645819622518ecb4dd41109f3a62008c269c085f6372797074616e656474797
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c7995cf3ba831d9763050000000403590ced403cf1952470b4d3c91ab18b1d5a711eb4fa528f
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