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Crypto-Conditions
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Abstract

The crypto-conditions specification defines a set of encoding formats and data structures for *conditions* and *fulfillments*. A condition uniquely identifies a logical "boolean circuit" constructed from one or more logic gates, evaluated by either validating a cryptographic signature or verifying the preimage of a hash digest. A fulfillment is a data structure encoding one or more cryptographic signatures and hash digest preimages that define the structure of the circuit and provide inputs to the logic gates allowing for the result of the circuit to be evaluated.

A fulfillment is validated by evaluating that the circuit output is TRUE but also that the provided fulfillment matches the circuit fingerprint, the condition.

Since evaluation of some of the logic gates in the circuit (those that are signatures) also take a message as input the evaluation of the entire fulfillment takes an optional input message which is passed to each logic gate as required. As such the algorithm to validate a fulfillment against a condition and a message matches that of other signature schemes and a crypto-condition can serve as a sophisticated and flexible replacement for a simple signature where the condition is used as the public key and the fulfillment as the signature.

Feedback

This specification is a part of the Interledger Protocol [1] work. Feedback related to this specification should be sent to ledger@ietf.org [2].

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

Crypto-conditions is a scheme for composing signature-like structures from one or more existing signature schemes or hash digest primitives. It defines a mechanism for these existing primitives to be combined and grouped to create complex signature arrangements but still maintain the useful properties of a simple signature, most notably, that a deterministic algorithm exists to verify the signature against a message given a public key.

Using crypto-conditions, existing primitives such as RSA and ED25519 signature schemes and SHA256 digest algorithms can be used as logic gates to construct complex boolean circuits which can then be used as compound signatures. The validation function for these compound signatures takes as input the fingerprint of the circuit, called the condition, the circuit definition and minimum required logic gates with their inputs, called the fulfillment, and a message.

The function returns a boolean indicating if the compound signature is valid or not. This property of crypto-conditions means they can be used in most scenarios as a replacement for existing signature schemes which also take as input, a public key (the condition), a signature (the fulfillment), and a message and return a boolean result.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Types

Crypto-conditions are a standard format for expressing conditions and fulfillments. The format supports multiple algorithms, including different hash functions and cryptographic signing schemes. Crypto-conditions can be nested in multiple levels, with each level possibly having multiple signatures.

The different types of crypto-conditions each have different internal strutures and employ different cryptographic algorithms as primitives.

3.1. Simple and Compound Types

Two categories of crypto-condition type exist. Simple crypto-conditions provide a standard encoding of common cryptographic primitives with hardcoded parameters, e.g RSA and ED25519 signature or SHA256 hash digests. As such, simple types that use the same underlying scheme (e.g. SHA) with different parameters (e.g. 256 or 512 bits) are considered different crypto-condition types.

As an example, the types defined in this version of the specification all use the SHA-256 digest algorithm to generate the condition fingerprint. If a future version were to introduce SHA-512 as an alternative this would require that new types be defined for each existing type that must have its condition generated using SHA-512.

Compound crypto-conditions contain one or more sub-crypto-conditions. The compound crypto-condition will evaluate to TRUE or FALSE based on the output of the evaluation of the sub-crypto-conditions. In this way compound crypto-conditions are used to construct branches of a boolean circuit.

To validate a compound crypto-condition all sub-crypto-conditions are provided in the fulfillment so that the fingerprint of the compound condition can be generated. However, some of these sub-crypto-conditions may be sub-fulfillments and some may be sub-conditions, depending on the type and properties of the compound crypto-condition.

As an example, in the case of an m-of-n signature scheme, only m sub-fulfillments are needed to validate the compound signature, but the remaining n-m sub-conditions must still be provided to validate that the complete fulfillment matches the originally provided condition. This is an important feature for multi-party signing, when not all parties are ready to provide fulfillment yet all parties still desire fulfillment of the overall condition if enough counter-parties do provide fulfillment.

3.2. Defining and Supporting New types

The crypto-conditions format has been designed so that it can be expanded. For example, you can add new cryptographic signature schemes or hash functions. This is important because advances in cryptography frequently render old algorithms insecure or invent newer, more effective algorithms.

Implementations are not required to support all condition types therefore it is necessary to indicate which types an implementation must support in order to validate a fulfillment. For this reason, compound conditions are encoded with an additional field, subtypes, indicating the set of types and subtypes of all sub-crypto-conditions.

4. Features

Crypto-conditions offer many of the features required of a regular signature scheme but also others which make them useful in a variety of new use cases.

4.1. Multi-Algorithm

Each condition type uses one or more cryptographic primitives such as digest or signature algorithms. Compound types may contain sub-crypto-conditions of any type and indicate the set of underlying types in the subtypes field of the condition

To verify that a given implementation can verify a fulfillment for a given condition, implementations MUST ensure they are able to validate fulfillments of all types indicated in the subtypes field of a compound condition. If an implementation encounters an unknown type it MUST reject the condition as it will almost certainly be unable to validate the fulfillment.

4.2. Multi-Signature

Crypto-conditions can abstract away many of the details of multi-sign. When a party provides a condition, other parties can treat it opaquely and do not need to know about its internal structure. That allows parties to define arbitrary multi-signature setups without breaking compatibility. That said, it is important that implementations must inspect the types and subtypes of any crypto-conditions they encounter to ensure they do not pass on a condition they will not be able to verify at a later stage.

In many instances protocol designers can use crypto-conditions as a drop-in replacement for public key signature algorithms and add

multi-signature support to their protocols without adding any additional complexity.

4.3. Multi-Level

Crypto-conditions elegantly support weighted multi-signatures and multi-level signatures. A threshold condition has a number of subconditions, and a target threshold. Each subcondition can be a signature or another threshold condition. This provides flexibility in forming complex conditions.

For example, consider a threshold condition that consists of two subconditions, one each from Wayne and Alf. Alf’s condition can be a signature condition while Wayne’s condition is a threshold condition, requiring both Claude and Dan to sign for him.

Multi-level signatures allow more complex relationships than simple M-of-N signing. For example, a weighted condition can support an arrangement of subconditions such as, "Either Ron, Mac, and Ped must approve; or Smithers must approve."

4.4. Crypto-conditions as a signature scheme

Crypto-conditions is a signature scheme for compound signatures which has similar properties to most other signature schemes, such as:

1. Validation of the signature (the fulfillment) is done using a public key (the condition) and a message as input

2. The same public key can be used to validate multiple different signatures, each against a different message

3. It is not possible to derive the signature from the public key

However, the scheme also has a number of features that make it unique such as:

1. It is possible to derive the same public key from any valid signature without the message

2. It is possible for the same public key and message to be used to validate multiple signatures. For example, the fulfillment of an m-of-n condition will be different for each combination of n signatures.

3. Composite signatures use one or more other signatures as components allowing for recursive signature validation logic to be defined.

4. A valid signature can be produced using different combinations of private keys if the structure of the compound signature requires only specific combinations of internal signatures to be valid (m of n signature scheme).

4.5. Crypto-conditions as a trigger in distributed systems

One of the challenges facing a distributed system is achieving atomic execution of a transaction across the system. A common pattern for solving this problem is two-phase commit in which the most time and resource-consuming aspects of the transaction are prepared by all participants following which a simple trigger is sufficient to either commit or abort the transaction. Described in more abstract terms, the system consists of a number of participants that have prepared a transaction pending the fulfillment of a predefined condition.

Crypto-conditions defines a mechanism for expressing these triggers as pairs of unique trigger identifiers (conditions) and cryptographically verifiable triggers (fulfillments) that can be deterministically verified by all participants.

It is also important that all participants in such a distributed system are able to evaluate, prior to the trigger being fired, that they will be capable of verifying the trigger. Determinism is useless if validation of the trigger requires algorithms or resources that are not available to all participants.

Therefore conditions may be used as *distributable event descriptions* in the form of a _fingerprint_, but also _event meta-data_ that allows the event verification system to determine if they have the necessary capabilities (such as required crypto-algorithms) and resources (such as heap size or memory) to verify the event notification later.

Fulfillments are therefore *cryptographically verifiable event notifications* that can be used to verify the event occurred but also that it matches the given description.

When using crypto-conditions as a trigger it will often make sense for the message that is used for validation to be empty to match the signature of the trigger processing system’s API. This makes crypto-conditions compatible with systems that use simple hash-locks as triggers.

If a PKI signature scheme is being used for the triggers this would require a new key pair for each trigger which is impractical. Therefore the PREFIX compound type wraps a sub-crypto-condition with a message prefix that is applied to the message before signature

validation. In this way a unique condition can be derived for each trigger even if the same key pair is re-used with an empty message.

4.6. Smart signatures

In the Interledger protocol, fulfillments provide non-repudiable proof that a transaction has been completed on a ledger. They are simple messages that can be easily shared with other ledgers. This allows ledgers to escrow funds or hold a transfer conditionally, then execute the transfer automatically when the ledger sees the fulfillment of the stated condition. In this way the Interledger protocol synchronizes multiple transfers on distinct ledgers in an almost atomic end-to-end transaction.

Crypto-conditions may also be useful in other contexts where a system needs to make a decision based on predefined criteria, and the proof from a trusted oracle(s) that the criteria have been met, such as smart contracts.

The advantage of using crypto-conditions for such use cases as opposed to a turing complete contract scripting language is the fact that the outcome of a crypto-condition validation is deterministic across platforms as long as the underlying cryptographic primitives are correctly implemented.

5. Validation of a fulfillment

Validation of a fulfillment (F) against a condition (C) and a message (M), in the majority of cases, follows these steps:

1. The implementation must derive a condition from the fulfillment and ensure that the derived condition (D) matches the given condition (C).

2. If the fulfillment is a simple crypto-condition AND is based upon a signature scheme (such as RSA-PSS or ED25519) then any signatures in the fulfillment (F) must be verified, using the appropriate signature verification algorithm, against the corresponding public key, also provided in the fulfillment and the message (M) (which may be empty).

3. If the fulfillment is a compound crypto-condition then the sub-fulfillments MUST each be validated. In the case of the PREFIX-SHA-256 type the sub-fulfillment MUST be valid for F to be valid and in the case of the THRESHOLD-SHA-256 type the number of valid sub-fulfillments must be equal or greater than the threshold defined in F.

If the derived condition (D) matches the input condition (C) AND the boolean circuit defined by the fulfillment evaluates to TRUE then the fulfillment (F) fulfills the condition (C).

A more detailed validation algorithm for each crypto-condition type is provided with the details of the type later in this document. In each case the notation F.x or C.y implies; the decoded value of the field named x of the fulfillment and the decoded value of the field named y of the Condition respectively.

5.1. Subfulfillments

In validating a fulfillment for a compound crypto-condition it is necessary to validate one or more sub-fulfillments per step 3 above. In this instance the condition for one or more of these sub-fulfillments is often not available for comparison with the derived condition. Implementations MUST skip the first fulfillment validation step as defined above and only perform steps 2 and 3 of the validation.

The message (M) used to validate sub-fulfillments is the same message (M) used to validate F however in the case of the PREFIX-SHA-256 type this is prefixed with F.prefix before validation of the sub-fulfillment is performed.

6. Deriving the Condition

Since conditions provide a unique fingerprint for fulfillments it is important that a determinisitic algorithm is used to derive a condition. For each crypto-condition type details are provided on how to:

1. Assemble the fingerprint content and calculate the hash digest of this data.

2. Calculate the maximum cost of validating a fulfillment

For compound types the fingerprint content will contain the complete, encoded, condition for all sub-crypto-conditions. Implementations MUST abide by the ordering rules provided when assembling the fingerprint content.

When calculating the fingerprint of a compound crypto-condition implementations MUST first derive the condition for all sub-fulfillments and include these conditions when assembling the fingerprint content.

6.1. Conditions as Public Keys

Since the condition is just a fingerprint and meta-data about the crypto-condition it can be transmitted freely in the same way a public key is shared publicly. It’s not possible to derive the fulfillment from the condition.

7. Format

A description of crypto-conditions is provided in this document using Abstract Syntax Notation One (ASN.1) as defined in [itu.X680.2015].

7.1. Encoding Rules

Implementations of this specificiation MUST support encoding and decoding using Distinguished Encoding Rules (DER) as defined in [itu.X690.2015]. This is the canonical encoding format.

Alternative encodings may be used to represent top-level conditions and fulfillments but to ensure a determinisitic outcome in producing the condition fingerprint content, including any sub-conditions, MUST be DER encoded prior to hashing.

The exception is the PREIMAGE-SHA-256 condition where the fingerprint content is the raw preimage which is not encoded prior to hashing. This is to allow a PREIMAGE-SHA-256 crypto-condition to be used in systems where "hash-locks" are already in use.

7.2. Condition

The binary encoding of conditions differs based on their type. All types define at least a fingerprint and cost sub-field. Some types, such as the compound condition types, define additional sub-fields that are required to convey essential properties of the crypto-condition (such as the sub-types used by sub-conditions in the case of the compound types).

Each crypto-condition type has a type ID. The list of known types is the IANA-maintained Crypto-Condition Type Registry (Appendix E.1).

Conditions are encoded as follows:

```
Condition ::= CHOICE {
  preimageSha256   [0] SimpleSha256Condition,
  prefixSha256     [1] CompoundSha256Condition,
  thresholdSha256  [2] CompoundSha256Condition,
  rsaSha256        [3] SimpleSha256Condition,
  ed25519Sha256    [4] SimpleSha256Condition
}

SimpleSha256Condition ::= SEQUENCE {
  fingerprint          OCTET STRING (SIZE(32)),
  cost                 INTEGER (0..4294967295)
}

CompoundSha256Condition ::= SEQUENCE {
  fingerprint          OCTET STRING (SIZE(32)),
  cost                 INTEGER (0..4294967295),
  subtypes             ConditionTypes
}

ConditionTypes ::= BIT STRING {
  preImageSha256   (0),
  prefixSha256     (1),
  thresholdSha256  (2),
  rsaSha256        (3),
  ed25519Sha256    (4)
}
```

7.2.1. Fingerprint

The fingerprint is an octet string uniquely representing the condition with respect to other conditions *of the same type*.

Implementations which index conditions MUST use the complete encoded condition as the key, not just the fingerprint - as different conditions of different types may have the same fingerprint.

For most condition types, the fingerprint is a cryptographically secure hash of the data which defines the condition, such as a public key.

For types that use PKI signature schemes, the signature is intentionally not included in the content that is used to compose the fingerprint. This means the fingerprint can be calculated without needing to know the message or having access to the private key.

Future types may use different functions to produce the fingerprint, which may have different lengths, therefore the field is encoded as a variable length string.

7.2.2. Cost

For each type, a cost function is defined which produces a determinsitic cost value based on the properties of the condition.

The cost functions are designed to produce a number that will increase rapidly if the structure and properties of a crypto-condition are such that they increase the resource requirements of a system that must validate the fulfillment.

The constants used in the cost functions are selected in order to provide some consistency across types for the cost value and the expected "real cost" of validation. This is not an exact science given that some validations will require signature verification (such as RSA and ED25519) and others will simply require hashing and storage of large values therefore the cost functions are roughly configured (through selection of constants) to be the number of bytes that would need to be processed by the SHA-256 hash digest algorithm to produce the equivalent amount of work.

The goal is to produce an indicative number that implementations can use to protect themselves from attacks involving crypto-conditions that would require massive resources to validate (denial of service type attacks).

Since dynamic heuristic measures can’t be used to achieve this a deterministic value is required that can be produced consistently by any implementation, therefore for each crypto-condition type, an algorithm is provided for consistently calculating the cost.

Implementations MUST determine a safe cost ceiling based on the expected cost value of crypto-conditions they will need to process. When a crypto-condition is submitted to an implementation, the implementation MUST verify that it will be able to process a fulfillment with the given cost (i.e. the cost is lower than the allowed ceiling) and reject it if not.

Cost function constants have been rounded to numbers that have an efficient base-2 representation to facilitate efficient arithmetic operations.

7.2.3. Subtypes

Subtypes is a bitmap that indicates the set of types an implementation must support in order to be able to successfully validate the fulfillment of this condition. This is the set of types and subtypes of all sub-crypto-conditions, recursively excluding the type of the root crypto-condition.

It must be possible to verify that all types used in a crypto-condition are supported (including the types and subtypes of any sub-crypto-conditions) even if the fulfillment is not available to be analysed yet. Therefore, all compound conditions set the bits in this bitmap that correspond to the set of types and subtypes of all sub-crypto-conditions.

The field is encoded as a variable length BIT STRING, as defined in ASN.1, to accommodate new types that may be defined.

Each bit in the bitmap represents a type from the list of known types in the IANA-maintained Crypto-Condition Type Registry (Appendix E.1) and the bit corresponding to each type is the bit at position X where X is the type ID of the type.

The presence of one or more sub-crypto-conditions of a specific type is indicated by setting the numbered bit corresponding to the type ID of that type.

In DER encoding, the bits in a bitstring are numbered from the MOST significant bit (bit 0) to least significant (bit 7) of the first byte and then continue with the MOST significant bit (bit 8) of the next byte, and so on. For example, a compound condition that contains an ED25519-SHA-256 crypto-condition as a sub-crypto-condition will set the bit at position 4 and the BITSTRING will be DER encoded with an appropriate tag byte followed by the three bytes 0x02 0x03 and 0x80, where 0x02 indicates the length (2 bytes, the first being the padding indicator), 0x03 indicates that there are 3 padding bits in the last byte and 0x80 indicates the 5 bits in the string are set to 00001.

7.3. Fulfillment

The ASN.1 definition for fulfillments is defined as follows:

```
Fulfillment ::= CHOICE {
  preimageSha256   [0] PreimageFulfillment ,
  prefixSha256     [1] PrefixFulfillment,
  thresholdSha256  [2] ThresholdFulfillment,
  rsaSha256        [3] RsaSha256Fulfillment,
  ed25519Sha256    [4] Ed25519Sha512Fulfillment
}

PreimageFulfillment ::= SEQUENCE {
  preimage             OCTET STRING
}

PrefixFulfillment ::= SEQUENCE {
  prefix               OCTET STRING,
  maxMessageLength     INTEGER (0..4294967295),
  subfulfillment       Fulfillment
}

ThresholdFulfillment ::= SEQUENCE {
  subfulfillments      SET OF Fulfillment,
  subconditions        SET OF Condition
}

RsaSha256Fulfillment ::= SEQUENCE {
  modulus              OCTET STRING,
  signature            OCTET STRING
}

Ed25519Sha512Fulfillment ::= SEQUENCE {
  publicKey            OCTET STRING (SIZE(32)),
  signature            OCTET STRING (SIZE(64))
}
```

8. Crypto-Condition Types

The following condition types are defined in this version of the specification. While support for additional crypto-condition types may be added in the future and will be registered in the IANA maintained Crypto-Condition Type Registry (Appendix E.1), no other types are supported by this specification.

8.1. PREIMAGE-SHA-256

PREIMAGE-SHA-256 is assigned the type ID 0. It relies on the availability of the SHA-256 digest algorithm.

This type of condition is also called a "hashlock". By creating a hash of a difficult-to-guess 256-bit random or pseudo-random integer

it is possible to create a condition which the creator can trivially fulfill by publishing the random value. However, for anyone else, the condition is cryptographically hard to fulfill, because they would have to find a preimage for the given condition hash.

Implementations MUST ignore any input message when validating a PREIMAGE-SHA-256 fulfillment as the validation of this crypto-condition type only requires that the SHA-256 digest of the preimage, taken from the fulfillment, matches the fingerprint, taken from the condition.

8.1.1. Cost

The cost is the size, in bytes, of the *unencoded* preimage.

cost = preimage length

8.1.2. ASN.1

```
-- Condition Fingerprint
-- The PREIMAGE-SHA-256 condition fingerprint content is not DER encoded
-- The fingerprint content is the preimage

-- Fulfillment
PreimageFulfillment ::= SEQUENCE {
  preimage             OCTET STRING
}
```

8.1.3. Condition Format

The fingerprint of a PREIMAGE-SHA-256 condition is the SHA-256 hash of the *unencoded* preimage.

8.1.4. Fulfillment Format

The fulfillment simply contains the preimage (encoded into a SEQUENCE of one element for consistency).

8.1.5. Validating

A PREIMAGE-SHA-256 fulfillment is valid iff C.fingerprint is equal to the SHA-256 hash digest of F.

8.1.6. Example

```
examplePreimageCondition Condition ::=
  preimageSha256 : {
    fingerprint '7F83B165 7FF1FC53 B92DC181 48A1D65D FC2D4B1F A3D67728 4ADDD200
126D9069'H,
    cost         12
  }

examplePreimageFulfillment Fulfillment ::=
  preimageSha256 : {
    preimage '48656C6C 6F20576F 726C6421'H
  }
```

8.2. PREFIX-SHA-256

PREFIX-SHA-256 is assigned the type ID 1. It relies on the availability of the SHA-256 digest algorithm and any other algorithms required by its sub-crypto-condition as it is a compound crypto-condition type.

Prefix crypto-conditions provide a way to narrow the scope of other crypto-conditions that are used inside the prefix crypto-condition as a sub-crypto-condition.

Because a condition is the fingerprint of a public key, by creating a prefix crypto-condition that wraps another crypto-condition we can narrow the scope from signing an arbitrary message to signing a message with a specific prefix.

We can also use the prefix condition in contexts where there is an empty message used for validation of the fulfillment so that we can reuse the same key pair for multiple crypto-conditions, each with a different prefix, and therefore generate a unique condition and fulfillment each time.

Implementations MUST prepend the prefix to the provided message and will use the resulting value as the message to validate the sub-fulfillment.

8.2.1. Cost

The cost is the size, in bytes, of the *unencoded* prefix, plus the maximum message that will be accepted to be prefixed and validated by the subcondition, plus the cost of the sub-condition, plus the constant 1024.

```
cost = prefix.length (in bytes) + max_message_length + subcondition_cost + 1024
```

8.2.2. ASN.1

```
-- Condition Fingerprint
PrefixFingerprintContents ::= SEQUENCE {
  prefix               OCTET STRING,
  maxMessageLength     INTEGER (0..4294967295),
  subcondition         Condition
}

-- Fulfillment
PrefixFulfillment ::= SEQUENCE {
  prefix               OCTET STRING,
  maxMessageLength     INTEGER (0..4294967295),
  subfulfillment       Fulfillment
}
```

8.2.3. Condition Format

The fingerprint of a PREFIX-SHA-256 condition is the SHA-256 digest of the DER encoded fingerprint contents which are a SEQUENCE of:

prefix An arbitrary octet string which will be prepended to the message during validation of the sub-fulfillment.

maxMessageLength The maximum size, in bytes, of the message that will be accepted during validation of the fulfillment of this condition.

subcondition The condition derived from the sub-fulfillment of this crypto-condition.

8.2.4. Fulfillment Format

The fulfillment of a PREFIX-SHA-256 crypto-condition is a PrefixFulfillment which is a SEQUENCE of:

prefix An arbitrary octet string which will be prepended to the message during validation of the sub-fulfillment.

maxMessageLength The maximum size, in bytes, of the message that will be accepted during validation of the fulfillment of this condition.

subfulfillment A fulfillment that will be verified against the prefixed message.

8.2.5. Validating

A PREFIX-SHA-256 fulfillment is valid iff:

1. The size of M, in bytes, is less than or equal to F.maxMessageLength AND

2. F.subfulfillment is valid, where the message used for validation of f is M prefixed by F.prefix AND

3. D is equal to C

8.2.6. Example

```
examplePrefixCondition Condition ::=
  prefixSha256 : {
    fingerprint 'BB1AC526 0C0141B7 E54B26EC 2330637C 5597BF81 1951AC09 E744AD20
FF77E287'H,
    cost         1024,
    subtypes    { preimageSha256 }
  }

examplePrefixFulfillment Fulfillment ::=
  prefixSha256 : {
    prefix           ''H,
    maxMessageLength  0,
    subfulfillment    preimageSha256 : { preimage ''H }
  }

examplePrefixFingerprintContents PrefixFingerprintContents ::= {
  prefix           ''H,
  maxMessageLength  0,
  subcondition      preimageSha256 : {
    fingerprint      'E3B0C44298FC1C149AFBF4C8996FB92427AE41E4649B934CA495991B78
52B855'H,
    cost              0
  }
}
```

Note that the example given, while useful to demonstrate the structure, has less practical security value that the use of an RSA-SHA-256 or ED25519-SHA-256 subfulfillment. Since the subfulfillment is a PREIMAGE-SHA-256, the validation of which ignores the incoming message, as long as the prefix, maxMessagelength and preimage provided in the subfulfillment are correct, the parent PREFIX-SHA-256 fulfillment will validate.

In this case, wrapping the PREIMAGE-SHA-256 crypto-condition in the PREFIX-SHA-256 crypto-condition, has the effect of enforcing a message length of 0 bytes.

Note also, any change to the PREFIX-SHA-256 crypto-condition's prefix and maxMessageLength values result in a different fingerprint value, effectively namespacing the underlying preimage and re-hashing it. The result is a new crypto-condition with a new and unique fingerprint with no change to the underlying sub-crypto-condition.

8.3. THRESHOLD-SHA-256

THRESHOLD-SHA-256 is assigned the type ID 2. It relies on the availability of the SHA-256 digest algorithm and any other algorithms required by any of its sub-crypto-conditions as it is a compound crypto-condition type.

8.3.1. Cost

The cost is the sum of the F.threshold largest cost values of all sub-conditions, added to 1024 times the total number of sub-conditions.

```
cost = (sum of largest F.threshold subcondition.cost values) + 1024 * F.subcondi
tions.count
```

For example, if a threshold crypto-condition contains 5 sub-conditions with costs of 64, 64, 82, 84 and 84 and has a threshold of 3, the cost is equal to the sum of the largest three sub-condition costs (82 + 84 + 84 = 250) plus 1024 times the number of sub-conditions (1024 * 5 = 5120): 5370

8.3.2. ASN.1

```
-- Condition Fingerprint
ThresholdFingerprintContents ::= SEQUENCE {
  threshold            INTEGER (1..65535),
  subconditions        SET OF Condition
}

-- Fulfillment
ThresholdFulfillment ::= SEQUENCE {
  subfulfillments      SET OF Fulfillment,
  subconditions        SET OF Condition
}
```

8.3.3. Condition Format

The fingerprint of a THRESHOLD-SHA-256 condition is the SHA-256 digest of the DER encoded fingerprint contents which are a SEQUENCE of:

threshold A number that MUST be an integer in the range 1 ... 65535. In order to fulfill a threshold condition, the count of the sub-fulfillments MUST be equal to the threshold.

subconditions The set of sub-conditions, F.threshold of which MUST be satisfied by valid sub-fulfillments provided in the fulfillment. The SET of DER encoded sub-conditions is sorted according to the DER encoding rules for a SET, in lexicographic (big-endian) order, smallest first as defined in section 11.6 of [itu.X690.2015].

8.3.4. Fulfillment Format

The fulfillment of a THRESHOLD-SHA-256 crypto-condition is a ThresholdFulfillment which is a SEQUENCE of:

subfulfillments A SET OF fulfillments. The number of elements in this set is equal to the threshold therefore implementations must use the length of this SET as the threshold value when deriving the fingerprint of this crypto-condition.

subconditions A SET OF conditions. This is the list of unfulfilled sub-conditions. This list must be combined with the list of conditions derived from the subfulfillments and the combined list, sorted, and used as the subconditions value when deriving the fingerprint of this crypto-condition.

This may be an empty list.

8.3.5. Validating

A THRESHOLD-SHA-256 fulfillment is valid iff :

1. All F.subfulfillments are valid.

2. D is equal to C.

8.3.6. Example

```
exampleThresholdCondition Condition ::=
  thresholdSha256 : {
    fingerprint 'B4B84136 DF48A71D 73F4985C 04C6767A 778ECB65 BA7023B4 506823BE
EE7631B9'H,
    cost         1024,
    subtypes    { preimageSha256 }
  }

exampleThresholdFulfillment Fulfillment ::=
  thresholdSha256 : {
```

```
    subfulfillments { preimageSha256 : { preimage ''H } },
    subconditions   { }
  }

exampleThresholdFingerprintContents ThresholdFingerprintContents ::= {
  threshold 1,
  subconditions {
    preimageSha256 : {
      fingerprint 'E3B0C442 98FC1C14 9AFBF4C8 996FB924 27AE41E4 649B934C A495991
B 7852B855'H,
      cost         0
    }
  }
}

exampleThresholdCondition2 Condition ::=
  thresholdSha256 : {
    fingerprint '5A218ECE 7AC4BC77 157F04CB 4BC8DFCD 5C9D225A 55BD0AA7 60BCA2A4
F1773DC6'H,
    cost         2060,
    subtypes    { preimageSha256 }
  }

exampleThresholdFulfillment2 Fulfillment ::=
  thresholdSha256 : {
    subfulfillments { preimageSha256 : { preimage ''H } },
    subconditions {
      preimageSha256 : {
        fingerprint '7F83B165 7FF1FC53 B92DC181 48A1D65D FC2D4B1F A3D67728 4ADDD
200 126D9069'H,
        cost         12
      }
    }
  }

exampleThresholdFingerprintContents2 ThresholdFingerprintContents ::= {
  threshold 1,
  subconditions {
    preimageSha256 : {
      fingerprint 'E3B0C442 98FC1C14 9AFBF4C8 996FB924 27AE41E4 649B934C A495991
B 7852B855'H,
      cost         0
    },
    preimageSha256 : {
      fingerprint '7F83B165 7FF1FC53 B92DC181 48A1D65D FC2D4B1F A3D67728 4ADDD20
0 126D9069'H,
      cost         12
    }
  }
}
```

8.4. RSA-SHA-256

RSA-SHA-256 is assigned the type ID 3. It relies on the SHA-256 digest algorithm and the RSA-PSS signature scheme.

The signature algorithm used is RSASSA-PSS as defined in PKCS#1 v2.2. [RFC8017]

Implementations MUST NOT use the default RSASSA-PSS-params. Implementations MUST use the SHA-256 hash algorithm and therefore, the same algorithm in the mask generation algorithm, as recommended in [RFC8017]. The algorithm parameters to use, as defined in [RFC4055] are:

```
pkcs-1 OBJECT IDENTIFIER  ::=  { iso(1) member-body(2) us(840) rsadsi(113549) pk
cs(1) 1 }

id-sha256 OBJECT IDENTIFIER  ::=  { joint-iso-itu-t(2) country(16) us(840) organ
ization(1) gov(101) csor(3) nistalgorithm(4) hashalgs(2) 1 }

sha256Identifier AlgorithmIdentifier  ::=  {
  algorithm            id-sha256,
  parameters           nullParameters
}

id-mgf1 OBJECT IDENTIFIER  ::=  { pkcs-1 8 }

mgf1SHA256Identifier AlgorithmIdentifier  ::=  {
  algorithm            id-mgf1,
  parameters           sha256Identifier
}

rSASSA-PSS-SHA256-Params RSASSA-PSS-params ::=  {
  hashAlgorithm        sha256Identifier,
  maskGenAlgorithm     mgf1SHA256Identifier,
  saltLength           20,
  trailerField         1
}
```

8.4.1. RSA Keys

To optimize the RsaFulfillment, and enforce a public exponent value of 65537, only the RSA Public Key modulus is stored in the RsaFingerprintContents and RsaFulfillment.

The modulus is stored as an OCTET STRING representing an unsigned integer (i.e. no sign byte) in big-endian byte-order, the most significant byte being the first in the string.

Implementations MUST use moduli greater than 128 bytes (1017 bits) and smaller than or equal to 512 bytes (4096 bits.) Large moduli slow down signature verification which can be a denial-of-service vector. DNSSEC also limits the modulus to 4096 bits [RFC3110]. OpenSSL supports up to 16384 bits [OPENSSL-X509-CERT-EXAMPLES].

Implementations MUST use the value 65537 for the public exponent e as recommended in [RFC4871]. Very large exponents can be a DoS vector [LARGE-RSA-EXPONENTS] and 65537 is the largest Fermat prime, which has some nice properties [USING-RSA-EXPONENT-OF-65537].

The recommended modulus size as of 2016 is 2048 bits [KEYLENGTH-RECOMMENDATION]. In the future we anticipate an upgrade to 3072 bits which provides approximately 128 bits of security [NIST-KEYMANAGEMENT] (p. 64), about the same level as SHA-256.

8.4.2. Cost

The cost is the square of the RSA key modulus size (in bytes).

cost = (modulus size in bytes) ^ 2

8.4.3. ASN.1

```
-- Condition Fingerprint
RsaFingerprintContents ::= SEQUENCE {
  modulus              OCTET STRING
}

-- Fulfillment
RsaSha256Fulfillment ::= SEQUENCE {
  modulus              OCTET STRING,
  signature            OCTET STRING
}
```

8.4.4. Condition Format

The fingerprint of an RSA-SHA-256 condition is the SHA-256 digest of the DER encoded fingerprint contents which is a SEQUENCE of a single element, the modulus of the RSA Key Pair.

8.4.5. Fulfillment Format

The fulfillment of an RSA-SHA-256 crypto-condition is an RsaSha256Fulfillment which is a SEQUENCE of:

modulus The modulus of the RSA key pair used to sign and verify the signature provided.

signature An octet string representing the RSA signature on the message M.

Implementations MUST verify that the signature is numerically less than the modulus.

Note that the message that has been signed is provided separately. If no message is provided, the message is assumed to be an octet string of length zero.

8.4.6. Validating

An RSA-SHA-256 fulfillment is valid iff :

1. F.signature is valid for the message M, using the RSA public key with modulus = F.modulus and exponent = 65537 for verification.

2. D is equal to C.

8.4.7. Example

```
exampleRsaCondition Condition ::=
  rsaSha256 : {
    fingerprint 'B31FA820 6E4EA7E5 15337B3B 33082B87 76518010 85ED84FB 4DAEB247
BF698D7F'H,
    cost         65536
  }

exampleRsaSha256Fulfillment Fulfillment ::=
  rsaSha256 : {
    modulus   'E1EF8B24 D6F76B09 C81ED775 2AA262F0 44F04A87 4D43809D 31CEA612 F9
9B0C97 A8B43741
               53E3EEF3 D6661684 3E0E41C2 93264B71 B6173DB1 CF0D6CD5 58C58657 70
6FCF09 7F704C48
               3E59CBFD FD5B3EE7 BC80D740 C5E0F047 F3E85FC0 D7581577 6A6F3F23 C5
DC5E79 7139A688
               2E38336A 4A5FB361 37620FF3 663DBAE3 28472801 862F72F2 F87B202B 9C
89ADD7 CD5B0A07
               6F7C53E3 5039F67E D17EC815 E5B4305C C6319706 8D5E6E57 9BA6DE5F 4E
3E57DF 5E4E072F
               F2CE4C66 EB452339 73875275 9639F025 7BF57DBD 5C443FB5 158CCE0A 3D
36ADC7 BA01F33A
               0BB6DBB2 BF989D60 7112F234 4D993E77 E563C1D3 61DEDF57 DA96EF2C FC
685F00 2B638246
               A5B309B9'H,
    signature '48E8945E FE007556 D5BF4D5F 249E4808 F7307E29 511D3262 DAEF61D8 80
98F9AA 4A8BC062
               3A8C9757 38F65D6B F459D543 F289D73C BC7AF4EA 3A33FBF3 EC444044 79
11D722 94091E56
               1833628E 49A772ED 608DE6C4 4595A91E 3E17D6CF 5EC3B252 8D63D2AD D6
463989 B12EEC57
               7DF64709 60DF6832 A9D84C36 0D1C217A D64C8625 BDB594FB 0ADA086C DE
CBBDE5 80D424BF
               9746D2F0 C312826D BBB00AD6 8B52C4CB 7D47156B A35E3A98 1C973863 79
2CC80D 04A18021
               0A524158 65B64B3A 61774B1D 3975D78A 98B0821E E55CA0F8 6305D425 29
E10EB0 15CEFD40
               2FB59B2A BB8DEEE5 2A6F2447 D2284603 D219CD4E 8CF9CFFD D5498889 C3
780B59 DD6A57EF
               7D732620'H
  }

exampleRsaFingerprintContents RsaFingerprintContents ::= {
  modulus     'E1EF8B24 D6F76B09 C81ED775 2AA262F0 44F04A87 4D43809D 31CEA612 F9
9B0C97 A8B43741
               53E3EEF3 D6661684 3E0E41C2 93264B71 B6173DB1 CF0D6CD5 58C58657 70
6FCF09 7F704C48
               3E59CBFD FD5B3EE7 BC80D740 C5E0F047 F3E85FC0 D7581577 6A6F3F23 C5
DC5E79 7139A688
               2E38336A 4A5FB361 37620FF3 663DBAE3 28472801 862F72F2 F87B202B 9C
89ADD7 CD5B0A07
               6F7C53E3 5039F67E D17EC815 E5B4305C C6319706 8D5E6E57 9BA6DE5F 4E
3E57DF 5E4E072F
               F2CE4C66 EB452339 73875275 9639F025 7BF57DBD 5C443FB5 158CCE0A 3D
36ADC7 BA01F33A
               0BB6DBB2 BF989D60 7112F234 4D993E77 E563C1D3 61DEDF57 DA96EF2C FC
685F00 2B638246
               A5B309B9'H
}
```

8.5. ED25519-SHA256

ED25519-SHA-256 is assigned the type ID 4. It relies on the SHA-256 and SHA-512 digest algorithms and the ED25519 signature scheme.

The exact algorithm and encodings used for the public key and signature are defined in [I-D.irtf-cfrg-eddsa] as Ed25519. SHA-512 is used as the hashing function for this signature scheme.

8.5.1. Cost

The public key and signature are a fixed size therefore the cost for an ED25519 crypto-condition is fixed at 131072.

cost = 131072

8.5.2. ASN.1

```
-- Condition Fingerprint
Ed25519FingerprintContents ::= SEQUENCE {
  publicKey            OCTET STRING (SIZE(32))
}

-- Fulfillment
Ed25519Sha512Fulfillment ::= SEQUENCE {
  publicKey            OCTET STRING (SIZE(32)),
  signature            OCTET STRING (SIZE(64))
}
```

8.5.3. Condition Format

The fingerprint of an ED25519-SHA-256 condition is the SHA-256 digest of the DER encoded Ed25519 public key included as the only value within a SEQUENCE. While the public key is already very small and constant size, we wrap it in a SEQUENCE type and hash it for consistency with the other types.

8.5.4. Fulfillment

The fulfillment of an ED25519-SHA-256 crypto-condition is an Ed25519Sha512Fulfillment which is a SEQUENCE of:

publicKey An octet string containing the Ed25519 public key.

signature An octet string containing the Ed25519 signature.

8.5.5. Validating

An ED25519-SHA-256 fulfillment is valid iff :

1. F.signature is valid for the message M, given the ED25519 public key F.publicKey.

2. D is equal to C.

8.5.6. Example

```
exampleEd25519Condition Condition ::=
  ed25519Sha256 : {
    fingerprint ’799239AB A8FC4FF7 EABFBC4C 44E69E8B DFED9933 24E12ED6 4792ABE2
89CF1D5F’H,
    cost 131072
  }

exampleEd25519Fulfillment Fulfillment ::=
  ed25519Sha256 : {
    publicKey  ’D75A9801 82B10AB7 D54BFED3 C964073A 0EE172F3 DAA62325 AF021A68 F
707511A’H,
    signature  ’E5564300 C360AC72 9086E2CC 806E828A 84877F1E B8E5D974 D873E065 2
2490155
               5FB88215 90A33BAC C61E3970 1CF9B46B D25BF5F0 595BBE24 65514143 8
E7A100B’H
  }

exampleEd25519FingerprintContents Ed25519FingerprintContents ::= {
  publicKey    ’D75A9801 82B10AB7 D54BFED3 C964073A 0EE172F3 DAA62325 AF021A68 F
707511A’H
}
```

9. URI Encoding Rules

Conditions can be encoded as URIs per the rules defined in the Named Information specification, [RFC6920]. There are no URI encoding rules for fulfillments.

Applications that require a string encoding for fulfillments MUST use an appropriate string encoding of the DER encoded binary representation of the fulfillment. No string encoding is defined in this specification. For consistency with the URI encoding of conditions, BASE64URL is recommended as described in [RFC4648], Section 5.

The URI encoding is only used to encode top-level conditions and never for sub-conditions. The binary encoding is considered the canonical encoding.

9.1. Condition URI Format

Conditions are represented as URIs using the rules defined in [RFC6920] where the object being hashed is the DER encoded fingerprint content of the condition as described for the specific condition type.

While [RFC6920] allows for truncated hashes, implementations using the Named Information URI schemes for crypto-conditions MUST only use untruncated SHA-256 hashes (Hash Name: sha-256, ID: 1 from the "Named Information Hash Algorithm Registry" defined in [RFC6920]).

9.2. New URI Parameter Definitions

[RFC6920] established the IANA registry of "Named Information URI Parameter Definitions". This specification defines three new definitions that are added to that registry and passed in URI encoded conditions as query string parameters.

9.2.1. Parameter: Fingerprint Type (fpt)

The "type" parameter indicates the type of condition that is represented by the URI. The value MUST be one of the names from the Crypto-Condition Type Registry (Appendix E.1).

9.2.2. Parameter: Cost (cost)

The cost parameter is the cost of the condition that is represented by the URI.

9.2.3. Parameter: Subtypes (subtypes)

The subtypes parameter indicates the types of conditions that are subtypes of the condition represented by the URI. The value MUST be a comma-separated list of names from the Crypto-Condition Type Registry (Appendix E.1).

The subtypes list MUST exclude the type of the root crypto-condition. Specifically, the value of the "fpt" parameter should not appear in the list of subtypes.

For example, if a threshold condition contains another threshold condition as well as a prefix condition, then its URI query parameters would appear like this:

ni:///...?cost=30&fpt=threshold-sha-256&subtypes=prefix-sha-256

Notice that the "subtypes" parameter does not contain "threshold-sha-256" because that type is already indicated in the "fpt" parameter.

The commas in the list should be treated as reserved characters per [RFC3986] and MUST not be percent encoded when used as list delimiters in the subtypes parameter.

9.2.3.1. Subtype Parameter Value Ordering

The subtypes list MUST be ordered by the type id value of each type, in ascending lexicographical order. That is, "preimage-sha-256" MUST appear before "prefix-sha-256", which MUST appear before "threshold-sha-256", and so on.

9.3. Condition URI Parameter Ordering

The parameters of a condition URI MUST appear in ascending lexicographical order based upon the name of each parameter. For example, the "cost" parameter must appear before the "fpt" parameter, which must appear before the "subtypes" parameter.

10. Example Condition

An example condition (PREIMAGE-SHA-256):

```
0x00000000 A0 25 80 20 7F 83 B1 65 7F F1 FC 53 B9 2D C1 81 .%.....e...S.-..
0x00000010 48 A1 D6 5D FC 2D 4B 1F A3 D6 77 28 4A DD D2 00 H..].-K...w(J...
0x00000020 12 6D 90 69 81 01 0C                           .m.i...
```

```
ni:///sha-256;f4OxZX_x_FO5LcGBSKHWXfwtSx-j1ncoSt3SABJtkGk?fpt=preimage-sha-256&c
ost=12
```

The example has the following attributes:

Field	Value	Description
scheme	"ni:///"	The named information scheme.
hash function name	"sha-256"	The fingerprint is hashed with the SHA-256 digest function
fingerprint	"f4OxZX_x_FO5LcGBSKHWXfwtSx-j1ncoSt3SABJtkGk"	The fingerprint for this condition.
type	"preimage-sha-256"	This is a PREIMAGE-SHA-256 (Section 8.1) condition.
cost	"12"	The fulfillment payload is 12 bytes long, therefore the cost is 12.

11. References

11.1. Normative References

[I-D.irtf-cfrg-eddsa]
Josefsson, S. and I. Liusvaara, "Edwards-curve Digital Signature Algorithm (EdDSA)", draft-irtf-cfrg-eddsa-08 (work in progress), August 2016.

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International Telecommunications Union, "Information technology - ASN.1 encoding rules: Specification of Basic Encoding Rules (BER), Canonical Encoding Rules (CER) and Distinguished Encoding Rules (DER)", August 2015, <http://handle.itu.int/11.1002/1000/12483>.

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[RFC3986] Berners-Lee, T., Fielding, R., and L. Masinter, "Uniform Resource Identifier (URI): Generic Syntax", STD 66, RFC 3986, DOI 10.17487/RFC3986, January 2005, <https://www.rfc-editor.org/info/rfc3986>.

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[RFC4648] Josefsson, S., "The Base16, Base32, and Base64 Data Encodings", RFC 4648, DOI 10.17487/RFC4648, October 2006, <https://www.rfc-editor.org/info/rfc4648>.

[RFC6920] Farrell, S., Kutscher, D., Dannewitz, C., Ohlman, B., Keranen, A., and P. Hallam-Baker, "Naming Things with Hashes", RFC 6920, DOI 10.17487/RFC6920, April 2013, <https://www.rfc-editor.org/info/rfc6920>.

[RFC8017] Moriarty, K., Ed., Kaliski, B., Jonsson, J., and A. Rusch, "PKCS #1: RSA Cryptography Specifications Version 2.2", RFC 8017, DOI 10.17487/RFC8017, November 2016, <https://www.rfc-editor.org/info/rfc8017>.

11.2. Informative References

[KEYLENGTH-RECOMMENDATION]
"BlueKrypt - Cryptographic Key Length Recommendation", September 2015, <https://www.keylength.com/en/compare/>.

[LARGE-RSA-EXPONENTS]
"Imperial Violet - Very large RSA public exponents (17 Mar 2012)", March 2012, <https://www.imperialviolet.org/2012/03/17/rsados.html>.

[NIST-KEYMANAGEMENT]
Barker, E., Barker, W., Burr, W., Polk, W., and M. Smid, "NIST - Recommendation for Key Management - Part 1 - General (Revision 3)", July 2012, <http://csrc.nist.gov/publications/nistpubs/800-57/sp800-57_part1_rev3_general.pdf>.

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"OpenSSL - X509 certificate examples for testing and verification", July 2012, <http://fm4dd.com/openssl/certexamples.htm>.

[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>.

[RFC3110] Eastlake 3rd, D., "RSA/SHA-1 SIGs and RSA KEYs in the Domain Name System (DNS)", RFC 3110, DOI 10.17487/RFC3110, May 2001, <https://www.rfc-editor.org/info/rfc3110>.

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[USING-RSA-EXPONENT-OF-65537]
"Cryptography - StackExchange - Impacts of not using RSA exponent of 65537", November 2014, <https://crypto.stackexchange.com/questions/3110/impacts-of-not-using-rsa-exponent-of-65537>.

11.3. URIs

[1] https://interledger.org/

[2] mailto:ledger@ietf.org

[3] https://github.com/rfcs/crypto-conditions#test-vectors

[4] https://github.com/interledgerjs/five-bells-condition

[5] https://github.com/hyperledger/quilt/tree/master/crypto-conditions

[6] https://github.com/bigchaindb/cryptoconditions

[7] https://github.com/go-interledger/cryptoconditions

[8] https://github.com/jtremback/crypto-conditions

[9] https://github.com/libscott/cryptoconditions-hs

[10] http://www.iana.org/assignments/crypto-condition-types

Appendix A. Security Considerations

This specification has a normative dependency on a number of other specifications with extensive security considerations therefore the consideratons defined for SHA-256 hashing and RSA signatures in [RFC8017] and [RFC4055] and for ED25519 signatures in [I-D.irtf-cfrg-eddsa] must be considered.

The cost and subtypes values of conditions are provided to allow implementations to evaluate their ability to validate a fulfillment for the given condition later.

Appendix B. Test Values

Test vectors have been prepared at: https://github.com/rfcs/crypto-conditions#test-vectors [3]

Appendix C. Implementations

Implementations of this specification are known to be available in the following languages:

- JavaScript: https://github.com/interledgerjs/five-bells-condition [4]
- Java: https://github.com/hyperledger/quilt/tree/master/crypto-conditions [5]
- Python: https://github.com/bigchaindb/cryptoconditions [6]
- Go: https://github.com/go-interledger/cryptoconditions [7]
- Go: https://github.com/jtremback/crypto-conditions [8]
- Haskell: https://github.com/libscott/cryptoconditions-hs [9]

Appendix D. ASN.1 Module

```
 --<ASN1.PDU CryptoConditions.Condition, CryptoConditions.Fulfillment>--

   Crypto-Conditions DEFINITIONS AUTOMATIC TAGS ::= BEGIN

-- Conditions

Condition ::= CHOICE {
  preimageSha256   [0] SimpleSha256Condition,
  prefixSha256     [1] CompoundSha256Condition,
  thresholdSha256  [2] CompoundSha256Condition,
  rsaSha256        [3] SimpleSha256Condition,
  ed25519Sha256    [4] SimpleSha256Condition
}

SimpleSha256Condition ::= SEQUENCE {
  fingerprint          OCTET STRING (SIZE(32)),
  cost                 INTEGER (0..4294967295)
}

CompoundSha256Condition ::= SEQUENCE {
  fingerprint          OCTET STRING (SIZE(32)),
  cost                 INTEGER (0..4294967295),
  subtypes             ConditionTypes
}

ConditionTypes ::= BIT STRING {
  preImageSha256   (0),
  prefixSha256     (1),
  thresholdSha256  (2),
  rsaSha256        (3),
  ed25519Sha256    (4)
}

-- Fulfillments

Fulfillment ::= CHOICE {
  preimageSha256   [0] PreimageFulfillment ,
  prefixSha256     [1] PrefixFulfillment,
  thresholdSha256  [2] ThresholdFulfillment,
  rsaSha256        [3] RsaSha256Fulfillment,
  ed25519Sha256    [4] Ed25519Sha512Fulfillment
}

PreimageFulfillment ::= SEQUENCE {
  preimage             OCTET STRING
}
```

```
PrefixFulfillment ::= SEQUENCE {
  prefix               OCTET STRING,
  maxMessageLength     INTEGER (0..4294967295),
  subfulfillment       Fulfillment
}

ThresholdFulfillment ::= SEQUENCE {
  subfulfillments      SET OF Fulfillment,
  subconditions        SET OF Condition
}

RsaSha256Fulfillment ::= SEQUENCE {
  modulus              OCTET STRING,
  signature            OCTET STRING
}

Ed25519Sha512Fulfillment ::= SEQUENCE {
  publicKey            OCTET STRING (SIZE(32)),
  signature            OCTET STRING (SIZE(64))
}

-- Fingerprint Content

-- The PREIMAGE-SHA-256 condition fingerprint content is not DER encoded
-- The fingerprint content is the preimage

PrefixFingerprintContents ::= SEQUENCE {
  prefix               OCTET STRING,
  maxMessageLength     INTEGER (0..4294967295),
  subcondition         Condition
}

ThresholdFingerprintContents ::= SEQUENCE {
  threshold            INTEGER (1..65535),
  subconditions        SET OF Condition
}

RsaFingerprintContents ::= SEQUENCE {
  modulus              OCTET STRING
}

Ed25519FingerprintContents ::= SEQUENCE {
  publicKey            OCTET STRING (SIZE(32))
}

   END
```

Appendix E. IANA Considerations

E.1. Crypto-Condition Type Registry

The following initial entries should be added to the Crypto-Condition Type registry to be created and maintained at (the suggested URI) http://www.iana.org/assignments/crypto-condition-types [10]:

The following types are registered:

Type ID	Type Name
0	PREIMAGE-SHA-256
1	PREFIX-SHA-256
2	THRESHOLD-SHA-256
3	RSA-SHA-256
4	ED25519

Table 1: Crypto-Condition Types

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July 08, 2016

The Interledger Protocol
draft-thomas-interledger-00

Abstract

This document specifies the Interledger Protocol (ILP). It draws heavily from the definition of the Internet Protocol (IP) defined in [RFC0791]. The interledger protocol is the culmination of more than a decade of research in decentralized payment protocols. This work was started in 2004 by Ryan Fugger, augmented by the development of Bitcoin in 2008 and has involved numerous contributors since then.

Feedback

This specification is a part of the Interledger Project [1] work. Feedback related to this specification should be sent to public-interledger@w3.org [2].

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 (#intro)

Payment networks today are siloed and disconnected. Payments are relatively easy within one country or if the sender and recipient have accounts on the same network or ledger. However, sending from one ledger to another is often impossible. Where connections do exist, they are manual, slow, or expensive.

The Interledger Protocol provides for routing payments across different digital asset ledgers while isolating senders and receivers from the risk of intermediary failures. Secure multi-hop payments and automatic routing enables a global network of networks for different types of value that can connect any sender with any receiver.

1.1. Scope

The interledger protocol is intentionally limited in scope to provide the functions necessary to deliver a payment from a source to a destination over an interconnected system of ledgers. It includes minimal requirements for underlying ledgers and it does not include public key infrastructure, identity, liquidity management, or other services commonly found in payment protocols.

1.2. Definitions

1.2.1. Transfer

Change in ownership of some asset

1.2.2. Ledger

System which records transfers

1.2.3. Connector

System which relays transfers between two ledgers

1.2.4. Payment

An exchange of assets involving one or more transfers on different ledgers

1.3. Basic Concepts

On the Interledger there are two roles. A ledger is a system of accounts, with balances, and the role of the ledger is to record transfers which change the balances of the accounts on the ledger. A connector is a host holding a balance on two or more ledgers. Connectors trade a debit against their balance on one ledger for a credit against their balance on another as a means of facilitating the payment between the two ledgers.

1.4. Operation

The central functions of the interledger protocol are addressing hosts and securing payments across different ledgers.

Each host sending and receiving interledger payments has an interledger module that uses the addresses in the interledger header to transmit interledger payments toward their destinations. Interledger modules share common rules for interpreting addresses. The modules (especially in connectors) also have procedures for making routing decisions and other functions.

The interledger protocol uses transfer holds to ensure that senders' funds are either delivered to the destination account or returned to the sender's account. This mechanism is described in greater detail in the Section 2 and the Interledger Whitepaper [3].

The interledger protocol treats each interledger payment as an independent entity unrelated to any other interledger payment. There are no connections or channels (virtual or otherwise).

Interledger payments do not carry a dedicated time-to-live or remaining-hops field. Instead, the amount field acts as an implicit time-to-live: Each time the payment is forwarded, the forwarding connector will take some fee out of the inbound amount. Once a connector recognizes that the inbound amount is worth less (though not necessarily numerically smaller) than the destination amount in the ILP header, it will refuse to forward the payment.

2. Overview

2.1. Relation to Other Protocols

This protocol is called on by hosts through higher level protocol modules in an interledger environment. Interledger protocol modules call on local ledger protocols to carry the interledger payment to the next connector or destination account. In this context a ledger may be a small ledger owned by an individual or organization or a large public ledger such as Bitcoin.

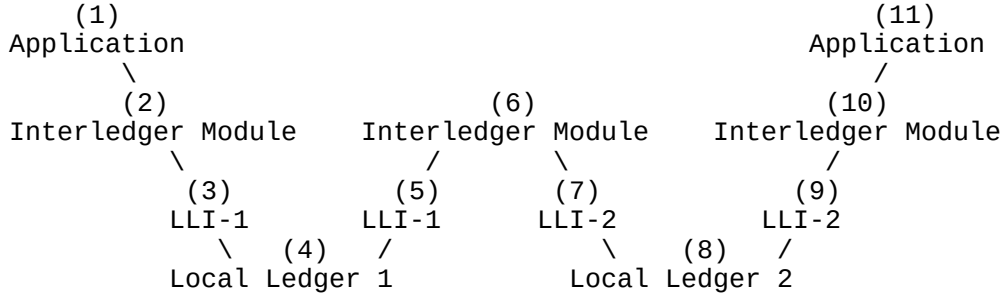
For example, a Simple Payment Setup Protocol (SPSP) [4] module would call the interledger module with the address and other parameters in the interledger packet to send a payment. The interledger module would send a transfer to the next connector or destination account along with the interledger packet and according to the parameters given. The transfer and interledger packet would be received by the next host's interledger module and handled by each each successive connector and finally the destination's SPSP module.

2.2. Model of Operation

2.2.1. Without Holds ("Optimistic Mode")

The protocol MAY be used without the security provided by holds - sometimes referred to as "Optimistic Mode". The model of operation for transmitting funds from one application to another without holds is illustrated by the following scenario:

We suppose the source and destination have accounts on different ledgers connected by a single connector.



1. The sending application chooses an amount and calls on its local interledger module to send that amount as a payment and passes the destination address and other parameters as arguments of the call.

2. The interledger module prepares an ILP packet and attaches the data to it. The interledger module determines a destination account on the local ledger for this interledger address. In this case it is the account of a connector. It passes the chosen amount and the local destination account to the local ledger interface.

3. The local ledger interface creates a local ledger transfer, then authorizes this transfer on the local ledger.

4. The ledger executes the transfer and notifies the connector.

5. The connector host’s local ledger interface receives the notification and passes it to the interledger module.

6. The connector’s interledger module extracts the ILP packet from the notification and determines from the interledger address that the payment is to be forwarded to another account in a second ledger. The interledger module converts the amount according to its locally available liquidity and determines the

local account on the other ledger corresponding to the destination host. It calls on the local ledger interface for the destination ledger to send the transfer, which includes the same ILP packet.

7. This local ledger interface creates a local ledger transfer and authorizes it.

8. The ledger executes the transfer and notifies the destination host.

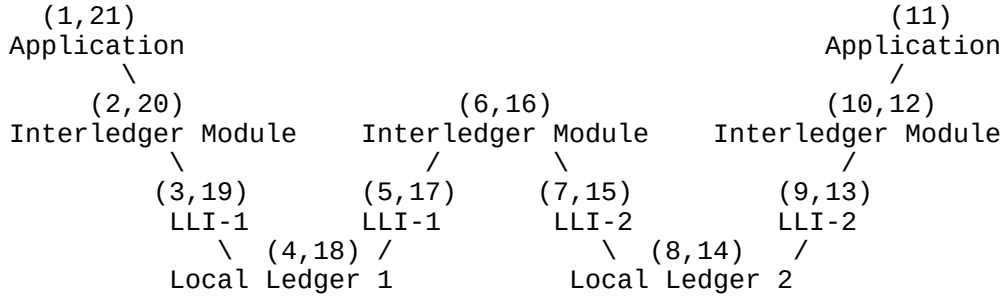
9. The destination host's local ledger interface receives the notification and passes it to the interledger module.

10. The interledger module extracts the ILP packet and determines that the payment is for an application in this host. It passes the transfer data to the application.

11. The destination application receives the notification of incoming funds and reacts accordingly.

2.2.1.1. With Holds ("Universal Mode")

The protocol MAY be used with transfer holds to ensure a sender's funds are delivered to the destination or returned to the sender's account. The model of operation is illustrated with the following example:



1. The sending application uses a higher-level protocol to negotiate the address, an amount, and a cryptographic condition with the destination. It calls on the interledger module to send a payment with these parameters.

2. The interledger module prepares the ILP packet, chooses the account to send the local ledger transfer to, and passes them to the local ledger interface.

3. The local ledger interface creates a local ledger transfer, including the crytographic condition, then authorizes this transfer on the local ledger.

4. The ledger puts the sender’s funds on hold - it does not transfer the funds to the connector - and notifies the connector.

5. The connector host’s local ledger interface receives the notification and passes it to the interledger module.

6. The connector’s interledger module extracts the ILP packet and determines that it should forward the payment. The interledger module calls on the destination ledger’s local ledger interface to send the second transfer, including the same condition as the sender’s transfer.

7. The local ledger interface creates a local ledger transfer, including the crytographic condition, then authorizes this transfer on the local ledger.

8. The ledger puts the connector’s funds on hold - it does not transfer the funds to the destination - and notifies the destination host.

9. The destination host’s local ledger interface receives the notification and passes it to the interledger module.

10. The interledger module extracts the ILP packet and determines that the payment is for an application in this host. It passes the transfer data to the application.

11. The destination application receives the notification and recognizes that funds are on hold pending the condition fulfillment. It checks the details of the incoming transfer against what was agreed upon with the sender. If checks pass, the application produces the condition fulfillment and passes it to the interledger module.

12. The destination’s interledger module passes the fulfillment to the local ledger interface.

13. The local ledger interface submits the fulfillment to the ledger.

14. The destination ledger validates the fulfillment against the held transfer’s condition. If the fulfillment is valid and the

transfer is not expired, the ledger executes the transfer and notifies the destination host and the connector.

15. The connector’s local ledger interface receives the fulfillment notification and passes it to the interledger module.

16. The connector’s interledger module receives the fulfillment and passes it to the local ledger interface corresponding to the source ledger.

17. This ledger interface submits the fulfillment to the source ledger.

18. The source ledger validates the fulfillment against the held transfer’s condition. If the fulfillment is valid and the transfer is not expired, the ledger executes the transfer and notifies the connector and the sender’s host.

19. The sender’s local ledger interface receives the fulfillment notification and passes it to the interledger module.

20. The sender’s interledger module receives the fulfillment notification and passes it to the application.

21. The sender’s application receives the fulfillment notification and reacts accordingly.

2.3. Function Description

The purpose of the interledger protocol is to enable hosts to route payments through an interconnected set of ledgers. This is done by passing the payments from one interledger module to another until the destination is reached. The interledger modules reside in hosts and connectors in the interledger system. The payments are routed from one interledger module to another through individual ledgers based on the interpretation of an interledger address. Thus, a central component of the interledger protocol is the interledger address.

When routing payments with relatively large amounts, the connectors and the intermediary ledgers they choose in the routing process may not be trusted. Holds provided by underlying ledgers MAY be used to protect the sender and receivers from this risk. In this case, the ILP packet contains a cryptographic condition and expiration date.

2.3.1. Addressing

As with the [RFC0791], interledger distinguishes between names, addresses, and routes. > "A name indicates what we seek. An address indicates where it is. A route indicates how to get there. The internet protocol deals primarily with addresses. It is the task of higher level (i.e., end-to-end or application) protocols to make the mapping from names to addresses."

The interledger module translates interledger addresses to local ledger addresses. Connectors and local ledger interfaces are responsible for translating addresses into interledger routes and local routes, respectively.

Addresses are hierarchically structured strings consisting of segments delimited by the period (".") character. In order to distinguish the present address format from future or alternative versions, the protocol prefix "ilp:" MUST be used:

"ilp:us.bank1.bob "

Care must be taken in mapping interledger addresses to local ledger accounts. Examples of address mappings may be found in "Address Mappings" ((TODO)).

2.3.2. Connectors

Connectors implement the interledger protocol to forward payments between ledgers. Connectors also implement other protocols to coordinate routing and other interledger control information.

2.4. Specification

2.4.1. ILP Header Format

Here is a summary of the fields in the ILP header format:

Field	Type	Short Description
version	INTEGER(0..255)	ILP protocol version (currently "1")
destinationAddress	IlpAddress	Address corresponding to the destination account
destinationAmount	IlpAmount	Amount the destination account should receive, denominated in the asset of the destination ledger
condition	OCTET STRING	See [draft-thomas-crypto-conditions-00]. The condition may be included in the packet or may be transmitted through the ledger layer.
expiresAt	IlpTimestamp	Maximum expiry time of the last transfer that the recipient will accept

2.4.1.1. version

INTEGER(0..255)

The version of the Interledger Protocol being used. This document describes version "1".

2.4.1.2. destinationAddress

IlpAddress :== SEQUENCE OF OCTET STRING

Hierarchical routing label.

2.4.1.3. destinationAmount

```
IlpAmount :== SEQUENCE { mantissa INTEGER, exponent INTEGER(-128..127) }
```

Base 10 encoded amount.

2.4.1.4. condition

IlpCondition :== Condition</code>

Crypto-condition in binary format as defined in [draft-thomas-crypto-conditions-00].

When processing a transfer carrying a condition a ledger MUST place a hold on the funds. While the funds are on hold, neither the sender nor recipient are able to access them. Upon receiving a condition fulfillment, a ledger MUST transfer the funds to the recipient if the funds are held, the fulfillment is a valid fulfillment of the transfer condition and the transfer has not yet expired. ("Universal Mode")

The condition is an optional field. If no condition is provided, the funds are immediately credited to the recipient of the transfer. ("Optimistic Mode")

2.4.1.5. expiresAt

IlpExpiry :== GeneralizedTime

Ledgers MAY require that all transfers with a condition also carry an expiry timestamp. Ledgers MUST reject transfers that carry an expiry timestamp, but no condition. Ledgers MUST reject transfers whose expiry transfer time has been reached or exceeded and whose condition has not yet been fulfilled. When rejecting a transfer, the ledger MUST lift the hold and make the funds available to the sender again.

2.5. Holds Without Native Ledger Support

Not all ledgers support held transfers. In the case of a ledger that doesn’t, the sender and recipient of the local ledger transfer MAY choose a commonly trusted party to carry out the hold functions. There are three options:

1. The sender MAY trust the receiver. The sender will perform a regular transfer in the first step and the receiver will perform a transfer back if the condition has not been met in time.

2. The receiver MAY trust the sender. The sender will notify the receiver about the intent to transfer. If the receiver provides a fulfillment for the condition before the expiry date, the sender will perform a regular transfer to the receiver.

3. The sender and receiver MAY appoint a mutually trusted third-party which has an account on the local ledger. The sender

performs a regular transfer into a neutral third-party account. In the first step, funds are transfered into the account belonging to the neutral third-party. ### Payment Channels

3. References

3.1. Normative References

[draft-thomas-crypto-conditions-00]
Thomas, S., "Crypto Conditions", July 2016.

3.2. Informative References

[RFC0791] Postel, J., "Internet Protocol", STD 5, RFC 791, DOI 10.17487/RFC0791, September 1981, <http://www.rfc-editor.org/info/rfc791>.

3.3. URIs

[1] https://interledger.org/interledger.pdf

[2] ../0009-simple-payment-setup-protocol/

Appendix A. Security Considerations

TODO

Appendix B. IANA Considerations

TODO

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