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V. Fuller
VAF.NET Internet Consulting
D. Lewis
V. Ermagan
Cisco Systems
A. Jain
Juniper Networks
A. Smirnov
Cisco Systems

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Locator/ID Separation Protocol Delegated Database Tree (LISP-DDT)

Abstract

This document describes the Locator/ID Separation Protocol Delegated Database Tree (LISP-DDT), a hierarchical distributed database that embodies the delegation of authority to provide mappings from LISP Endpoint Identifiers (EIDs) to Routing Locators (RLOCs). It is a statically defined distribution of the EID namespace among a set of LISP-speaking servers called "DDT nodes". Each DDT node is configured as "authoritative" for one or more EID-prefixes, along with the set of RLOCs for Map-Servers or "child" DDT nodes to which more-specific EID-prefixes are delegated.

Status of This Memo

This document is not an Internet Standards Track specification; it is published for examination, experimental implementation, and evaluation.

This document defines an Experimental Protocol for the Internet community. This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Not all documents approved by the IESG are a candidate for any level of Internet Standard; see Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at http://www.rfc-editor.org/info/rfc8111.

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1. Introduction

The Locator/ID Separation Protocol (LISP) [RFC6830] specifies an architecture and mechanism for replacing the addresses currently used by IP with two separate namespaces:

- Endpoint Identifiers (EIDs), used end to end for terminating transport-layer associations, and
- Routing Locators (RLOCs), which are bound to topological locations and are used for routing and forwarding through the Internet infrastructure.

[RFC6833] specifies an interface between a database storing EID-to-RLOC mappings and LISP devices that need this information for packet forwarding. The internal organization of such a database is beyond the scope of [RFC6833]. Multiple architectures of the database have been proposed, each having its advantages and disadvantages (see, for example, [RFC6836] and [RFC6837]).

This document specifies an architecture for a database of LISP EID-to-RLOC mappings, with an emphasis on high scalability. The LISP Delegated Database Tree (LISP-DDT) is a hierarchical distributed database that embodies the delegation of authority to provide mappings, i.e., its internal structure mirrors the hierarchical delegation of address space. It also provides delegation information to Map-Resolvers, which use the information to locate EID-to-RLOC mappings. A Map-Resolver that needs to locate a given mapping will follow a path through the tree-structured database and will contact, one after another, the DDT nodes along that path until it reaches the leaf DDT node(s) authoritative for the mapping it is seeking.

LISP offers a general-purpose mechanism for mapping between EIDs and RLOCs. In organizing a database of EID-to-RLOC mappings, this specification extends the definition of the EID numbering space by logically prepending and appending several fields for purposes of defining the database index key:

- Database-ID (DBID) (16 bits),
- Instance Identifier (IID) (32 bits),
- Address Family Identifier (AFI) (16 bits), and
- EID-prefix (variable, according to the AFI value).

The resulting concatenation of these fields is termed an "Extended EID-prefix", or XEID-prefix.

LISP-DDT defines a new device type, the DDT node, that is configured as authoritative for one or more XEID-prefixes. It is also configured with the set of more-specific sub-prefixes that are further delegated to other DDT nodes. To delegate a sub-prefix, the "parent" DDT node is configured with the RLOCs of each child DDT node that is authoritative for the sub-prefix. Each RLOC either points to a DDT Map-Server (MS) to which an Egress Tunnel Router (ETR) has registered that sub-prefix or points to another DDT node in the database tree that further delegates the sub-prefix. See [RFC6833] for a description of the functionality of the Map-Server and Map-Resolver. Note that the target of a delegation must always be an RLOC (not an EID) to avoid any circular dependency.

To provide a mechanism for traversing the database tree, LISP-DDT defines a new LISP message type, the Map-Referral, which is returned to the sender of a Map-Request when the receiving DDT node can refer the sender to another DDT node that has more detailed information. See Section 6 for the definition of the Map-Referral message.

To find an EID-to-RLOC mapping, a LISP-DDT client, usually a DDT Map-Resolver, starts by sending an Encapsulated Map-Request to a preconfigured DDT node RLOC. The DDT node responds with a Map-Referral message indicating that either (1) it will find the requested mapping to complete processing of the request or (2) the DDT client should contact another DDT node that has more-specific information; in the latter case, the DDT node then sends a new Encapsulated Map-Request to the next DDT node and the process repeats in an iterative manner.

Conceptually, this is similar to the way that a client of the Domain Name System (DNS) follows referrals (DNS responses that contain only NS records) from a series of DNS servers until it finds an answer.

2. Requirements Language

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

3. Definitions of Terms

Extended EID (XEID): a LISP EID extended with data uniquely identifying the address space to which it belongs (LISP IID, address family, etc.). See Section 4.1 for a detailed description of XEID data.

Extended EID-prefix (XEID-prefix): a LISP EID-prefix prepended with XEID data. An XEID-prefix is used as a key index into the DDT database. XEID-prefixes are used to describe database organization and are not seen as a single entity in protocol messages, though messages contain individual fields constituting XEID-prefixes.

DDT node: a network infrastructure component responsible for specific XEID-prefix(es) and for the delegation of more-specific sub-prefixes to other DDT nodes.

DDT client: a network infrastructure component that sends DDT Map-Request messages and implements the iterative following of Map-Referral results. Typically, a DDT client will be a Map-Resolver (as defined by [RFC6833]), but it is also possible for an Ingress Tunnel Router (ITR) to implement DDT client functionality.

DDT Map-Server: a DDT node that also implements Map-Server functionality (forwarding Map-Requests and/or returning Map-Replies if offering a proxy Map-Reply service) for a subset of its delegated prefixes. Map-Server functions, including proxying Map-Replies, are described in [RFC6833].

DDT Map-Server peers: a list of all DDT Map-Servers performing Map-Server functionality for the same prefix. If peers are configured on a DDT Map-Server, then the latter will provide complete information about the prefix in its Map-Replies; otherwise, the Map-Server will mark the returned reply as potentially incomplete.

DDT Map-Resolver: a network infrastructure element that implements both DDT client functionality and Map-Resolver functionality as defined by [RFC6833]. A DDT Map-Resolver accepts Map-Requests from ITRs, sends DDT Map-Requests to DDT nodes, and implements the iterative following of Map-Referrals. Note that Map-Resolvers do not respond to clients that sent Map-Requests; they only ensure that the Map-Request has been forwarded to a LISP device (ETR or proxy Map-Server) that will provide an authoritative response to the original requester. A DDT Map-Resolver will typically

maintain a cache (termed the "referral cache") of previously received Map-Referral message results containing RLOCs for DDT nodes responsible for XEID-prefixes of interest.

Encapsulated Map-Request: a LISP Map-Request that is carried within an Encapsulated Control Message and that has an additional LISP header prepended to it. Sent to UDP destination port 4342. The "outer" addresses are globally routable IP addresses, also known as RLOCs. Used by an ITR when sending a Map-Request to a Map-Resolver and by a Map-Server when forwarding a Map-Request to an ETR as documented in [RFC6833].

DDT Map-Request: an Encapsulated Map-Request sent by a DDT client to a DDT node. The "DDT-originated" flag is set in the encapsulation header, indicating that the DDT node should return Map-Referral messages if the Map-Request EID matches a delegated XEID-prefix known to the DDT node. Section 7.3.1 describes how DDT Map-Requests are sent. Section 5 defines the position of the "DDT-originated" flag in the Encapsulated Control Message header.

Authoritative XEID-prefix: an XEID-prefix delegated to a DDT node and for which the DDT node may provide further delegations of more-specific sub-prefixes.

Map-Referral: a LISP message sent by a DDT node in response to a DDT Map-Request for an XEID that matches a configured XEID-prefix delegation. A non-Negative Map-Referral includes a "referral" -- a set of RLOCs for DDT nodes that have information about the more-specific XEID-prefix covering the requested XEID; a DDT client "follows the referral" by sending another DDT Map-Request to one of those RLOCs to obtain either an answer or another referral to DDT nodes responsible for an XEID-prefix that is even more specific. See Sections 7.1 and 7.3.2 for details on the sending and processing of Map-Referral messages.

Negative Map-Referral: an answer from an authoritative DDT node that there is no mapping for the requested XEID. A Negative Map-Referral is a Map-Referral sent in response to a DDT Map-Request that matches an authoritative XEID-prefix but for which there is no delegation configured (or no ETR registration, if sent by a DDT Map-Server).

Pending Request List: the set of outstanding requests for which a DDT Map-Resolver has received Encapsulated Map-Requests from its clients seeking EID-to-RLOC mapping for an XEID. Each entry in the list contains additional state needed by the referral-following process, including the XEID, requester(s) of the XEID (typically one or more ITRs), saved information about the

last referral received and followed (matching XEID-prefix, action code, RLOC set, index of the last RLOC queried in the RLOC set), and any LISP-Security (LISP-SEC) information [LISP-SEC] that was included in the DDT client Map-Request. An entry in the list may be interchangeably termed a "pending request list entry" or simply a "pending request".

For definitions of other terms -- notably Map-Request, Map-Reply, ITR, ETR, Map-Server, and Map-Resolver -- please consult the LISP specification [RFC6830] and the LISP Mapping Service specification [RFC6833].

4. Database Organization

4.1. XEID-Prefixes

A DDT database is indexed by Extended EID-prefixes (XEID-prefixes). An XEID-prefix is a LISP EID-prefix, together with data extending it to uniquely identify the address space of the prefix. An XEID-prefix is composed of four binary-encoded fields, ordered by significance: DBID (16 bits), IID (32 bits), AFI (16 bits), and EID-prefix (variable, according to the AFI value). The fields are concatenated, with the most significant fields as listed above.

The DBID is the LISP-DDT Database-ID, a 16-bit field provided to allow the definition of multiple databases. Implementations that are compliant with this document must always set this field to 0. Other values of the DBID are reserved for future use.

The Instance ID (IID) is a 32-bit value describing the context of the EID-prefix, if the latter is intended for use in an environment where addresses may not be unique, such as in a Virtual Private Network where the [RFC1918] address space is used. See Section 5.5 of [RFC6830] for more discussion of IIDs. Encoding of the IID is specified by [RFC8060].

The AFI is a 16-bit value defining the syntax of the EID-prefix. AFI values are assigned by IANA [AFI].

4.2. Structure of the DDT Database

The LISP-DDT database for each DDT node is organized as a tree structure that is indexed by XEID-prefixes. Leaves of the database tree describe the delegation of authority between DDT nodes (see Section 4.3 for details regarding delegation and information kept in the database entries).

DDT Map-Requests sent by the DDT client to DDT nodes always contain specific values for the DBID, IID, and AFI; unspecified values or ranges of values are never used for any of these fields. Thus, an XEID-prefix used as a key for searches in the database tree will have a length of at least 64 bits.

A DDT node may, for example, be authoritative for a consecutive range of 3-tuples (DBID, IID, AFI) and all associated EID-prefixes, or only for a specific EID-prefix of a single 3-tuple. Thus, XEID-prefixes/keys of the database tree leaves may have lengths less than, equal to, or more than 64 bits.

It is important to note that LISP-DDT does not store actual EID-to-RLOC mappings; it is, rather, a distributed index that can be used to find the devices (ETRs that registered their EIDs with DDT Map-Servers) that can be queried with LISP to obtain those mappings. Changes to EID-to-RLOC mappings are made on the ETRs that define them, not to any DDT node configuration. DDT node configuration changes are only required when branches of the database hierarchy are added, removed, or modified.

4.3. Configuring Prefix Delegation

Every DDT node is configured with one or more XEID-prefixes for which it is authoritative, along with a list of delegations of XEID-prefixes to other DDT nodes. A DDT node is required to maintain a list of delegations for all sub-prefixes of its authoritative XEID-prefixes; it also may list "hints", which are prefixes that it knows about that belong to its parents, to the root, or to any other point in the XEID-prefix hierarchy. A delegation (or hint) consists of an XEID-prefix, a set of RLOCs for DDT nodes that have more detailed knowledge of the XEID-prefix, and accompanying security information (for details regarding security information exchange and its use, see Section 10). Those RLOCs are returned in Map-Referral messages when the DDT node receives a DDT Map-Request with an XEID that matches a delegation. A DDT Map-Server will also have a set of sub-prefixes for which it accepts ETR mapping registrations and for which it will forward (or answer, if it provides a proxy Map-Reply service) Map-Requests.

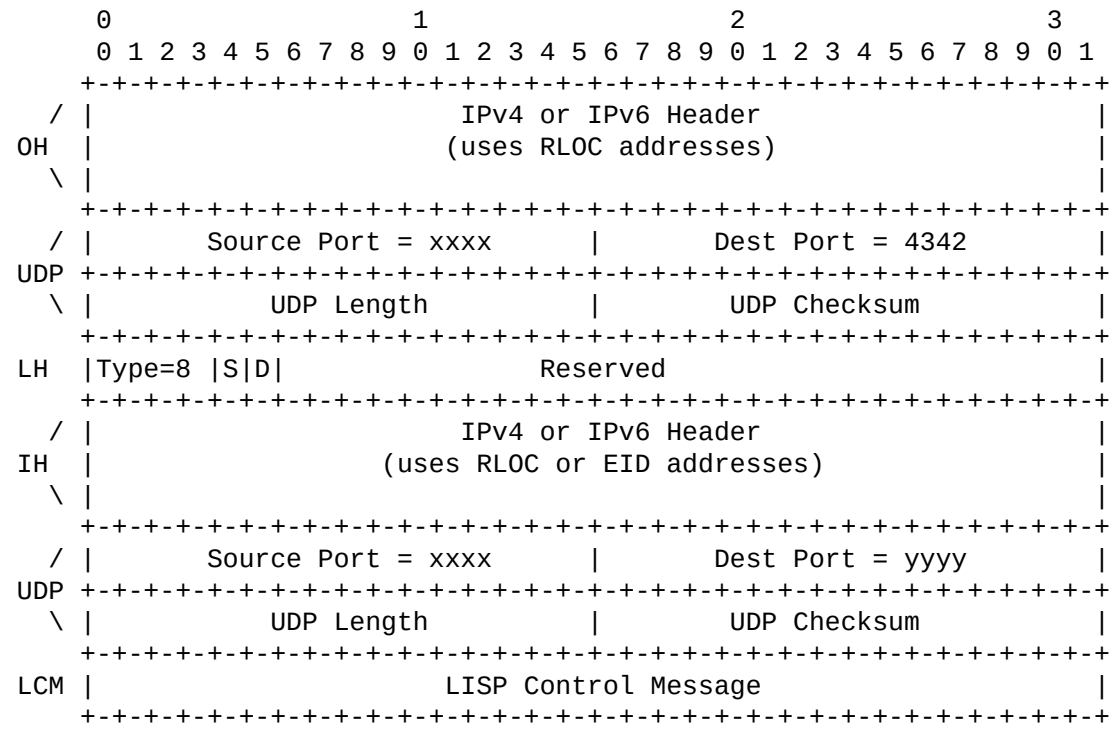
One or more XEID-prefixes for which a DDT node is authoritative, and the delegation of authority for sub-prefixes, are provided as part of the configuration of the DDT node. Implementations will likely develop a language to express this prefix authority and delegation. Since DDT configuration is static (i.e., not exchanged between DDT nodes as part of the protocol itself), such language is implementation dependent and is outside the scope of this specification.

4.3.1. The Root DDT Node

The root DDT node is the logical "top" of the distributed database hierarchy. It is authoritative for all XEID-prefixes -- that is, for all valid 3-tuples (DBID, IID, AFI) and their EID-prefixes. A DDT Map-Request that matches no configured XEID-prefix will be referred to the root node (see Section 8 for a formal description of conditions where a DDT Map-Request is forwarded to the root node). The root node in a particular instantiation of LISP-DDT therefore MUST be configured, at a minimum, with delegations for all defined IIDs and AFIs.

5. DDT Map-Request

A DDT client (usually a Map-Resolver) uses LISP Encapsulated Control Messages (ECMs) to send Map-Request messages to a DDT node. The format of the ECM is defined by [RFC6830]. This specification adds to the Encapsulated Control Message (ECM) header a new flag, "DDT-originated", as shown in the diagram and described below.



D: The "DDT-originated" flag. This flag is set by a DDT client to indicate that the receiver SHOULD return Map-Referral messages as appropriate. The use of this flag is further described in Section 7.3.1. This bit is allocated from LISP message header bits marked as "Reserved" in [RFC6830].

6. The Map-Referral Message

This specification defines a new LISP message called the Map-Referral message. A Map-Referral message is sent by a DDT node to a DDT client in response to a DDT Map-Request message. See Section 6.4 for a detailed layout of the Map-Referral message fields.

The message consists of an action code along with delegation information about the XEID-prefix that matches the requested XEID.

6.1. Action Codes

The action codes are as follows:

NODE-REFERRAL (0): indicates that the replying DDT node has delegated an XEID-prefix that matches the requested XEID to one or more other DDT nodes. The Map-Referral message contains a "map-record" with additional information -- most significantly, the set of RLOCs to which the prefix has been delegated -- that is used by a DDT client to "follow" the referral.

MS-REFERRAL (1): indicates that the replying DDT node has delegated an XEID-prefix that matches the requested XEID to one or more DDT Map-Servers. It contains the same additional information as a NODE-REFERRAL but is handled slightly differently by the receiving DDT client (see Section 7.3.2).

MS-ACK (2): indicates that the replying DDT Map-Server received a DDT Map-Request that matches an authoritative XEID-prefix for which it has one or more registered ETRs. This means that the request has been forwarded to one of those ETRs to provide an answer to the querying ITR.

MS-NOT-REGISTERED (3): indicates that the replying DDT Map-Server received a Map-Request for one of its configured XEID-prefixes that has no ETRs registered.

DELEGATION-HOLE (4): indicates that the requested XEID matches a non-delegated sub-prefix of the XEID space. This is a non-LISP "hole", which has not been delegated to any DDT Map-Server or ETR. See Section 7.1.2 for details. Also sent by a DDT Map-Server with authoritative configuration covering the requested EID but for which no specific site ETR is configured.

NOT-AUTHORITATIVE (5): indicates that the replying DDT node received a Map-Request for an XEID for which it is not authoritative and has no configured matching hint referrals. This can occur if a cached referral has become invalid due to a change in the database hierarchy. However, if such a DDT node has a "hint" delegation covering the requested EID, it MAY choose to return NODE-REFERRAL or MS-REFERRAL as appropriate. When returning action code NOT-AUTHORITATIVE, the DDT node MUST provide the EID-prefix received in the request and the TTL MUST be set to 0.

6.2. Referral Set

For "positive" action codes (NODE-REFERRAL, MS-REFERRAL, MS-ACK), a DDT node MUST include in the Map-Referral message a list of RLOCs for DDT nodes that are authoritative for the XEID-prefix being returned; a DDT client uses this information to contact one of those DDT nodes as it "follows" a referral.

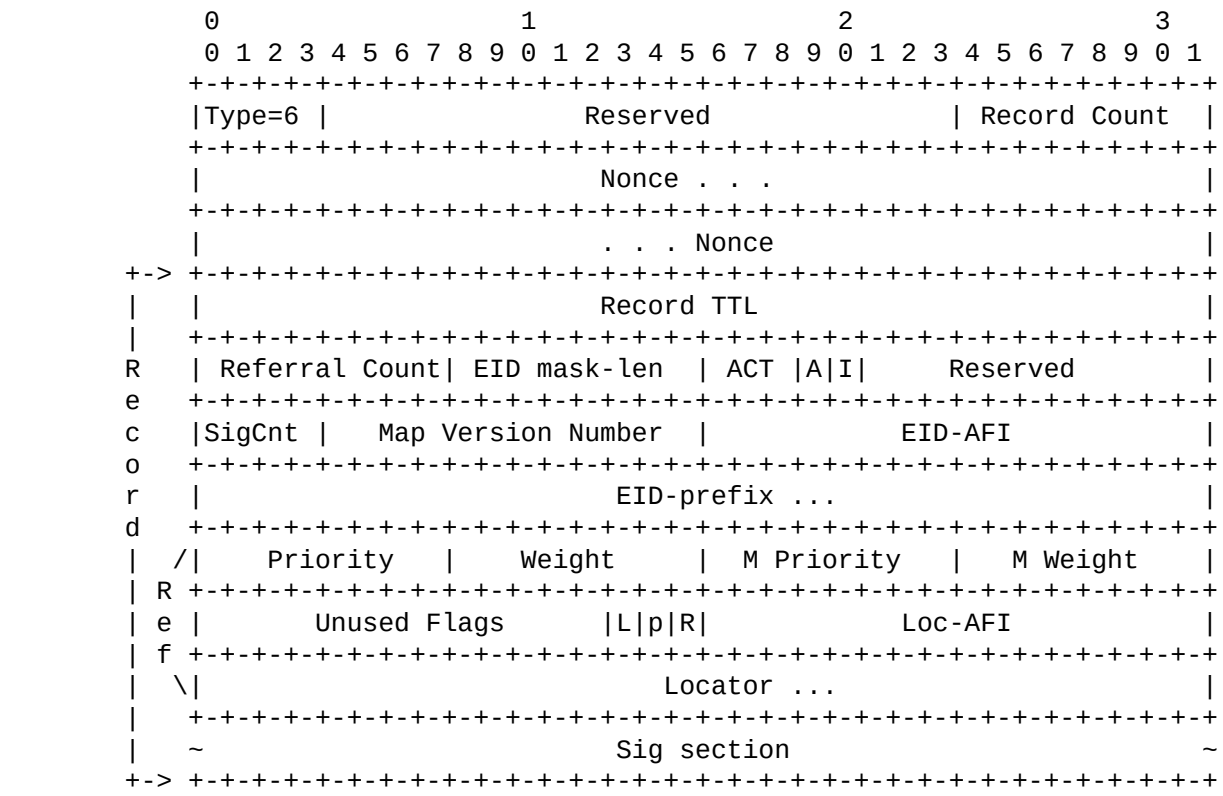
6.3. "Incomplete" Flag

A DDT node sets the "Incomplete" flag in a Map-Referral message if the Referral Set is incomplete; this is intended to prevent a DDT client from caching a referral with incomplete information. A DDT node MUST set the "Incomplete" flag in the following cases:

- If it is setting action code MS-ACK or MS-NOT-REGISTERED but the matching XEID-prefix is not flagged as "complete" in the configuration. The XEID-prefix configuration on the DDT Map-Server SHOULD be marked as "complete" when the configuration of the XEID-prefix lists all "peer" DDT nodes that are also authoritative for the same XEID-prefix or when it is known that a local DDT node is the only authoritative node for the XEID-prefix.

- If it is setting action code NOT-AUTHORITATIVE.

6.4. Map-Referral Message Format



Type: Type value 6 was reserved for future use in [RFC6830]. This document allocates this value to identify Map-Referral messages.

ACT: The ACT (Action) field of the mapping Record in a Map-Referral message encodes one of the following six action types: NODE-REFERRAL, MS-REFERRAL, MS-ACK, MS-NOT-REGISTERED, DELEGATION-HOLE, or NOT-AUTHORITATIVE. See Section 6.1 for descriptions of these action types.

Incomplete: The "I" bit indicates that a DDT node's Referral Set of locators is incomplete and the receiver of this message SHOULD NOT cache the referral. A DDT sets the "Incomplete" flag, the TTL, and the Action field as follows:

Type (Action field)		Incomplete Referral Set		TTL values
0	NODE-REFERRAL	No	Yes	1440
1	MS-REFERRAL	No	Yes	1440
2	MS-ACK	*	*	1440
3	MS-NOT-REGISTERED	*	*	1
4	DELEGATION-HOLE	No	No	15
5	NOT-AUTHORITATIVE	Yes	No	0

*: The "Incomplete" flag setting for the Map-Server-originated referral of MS-ACK and MS-NOT-REGISTERED types depends on whether the Map-Server has the full peer Map-Server configuration for the same prefix and has encoded the information in the mapping Record. The "Incomplete" bit is not set when the Map-Server has encoded the information; this means that the Referral Set includes all the RLOCs of all Map-Servers that serve the prefix. It MUST be set when the configuration of the Map-Server does not flag the matching prefix as configured with the complete information about "peer" Map-Servers or when the Map-Server does not return all configured locators.

Referral Count: Number of RLOCs in the current Referral Set. This number is equal to the number of "Ref" sections in the message (as shown in the diagram above).

SigCnt: Indicates the number of signatures (Signature section) present in the Record. If SigCnt is larger than 0, the signature information captured in a Signature section as described in Section 6.4.1 will be appended to the end of the Record. The number of Signature sections at the end of the Record MUST match the SigCnt. Note that bits occupied by SigCnt were marked as "Reserved" in Records embedded into messages defined by [RFC6830] and were required to be set to zero.

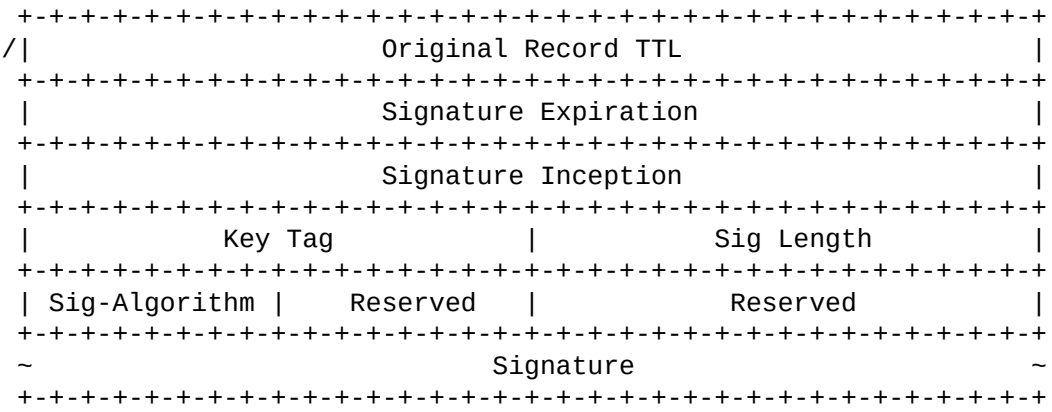
Loc-AFI: AFI of the Locator field. If the AFI value is different from the LISP Canonical Address Format (LCAF) AFI, security keys are not included in the Record. If the AFI value is equal to the LCAF AFI, the contents of the LCAF depend on the Type field of the LCAF. LCAF Type 11 is used to store security material along with the AFI of the locator. DDT nodes and DDT Map-Servers can use this LCAF Type to include public keys associated with their child DDT nodes for an XEID-prefix Map-Referral Record. LCAF Types and formats are defined in [RFC8060].

Locator: RLOC of a DDT node to which the DDT client is being referred. This is a variable-length field; its length is determined by the Loc-AFI setting.

All other fields and their descriptions are equivalent to those in the Map-Reply message, as defined in LISP [RFC6830]. Note, though, that the set of RLOCs correspond to the DDT node to be queried as a result of the referral and not to the RLOCs for an actual EID-to-RLOC mapping.

6.4.1. Signature Section

SigCnt counts the number of signature sections that appear at the end of the Record. The format of the signature section is described below.



Original Record TTL: The original Record TTL for this Record that is covered by the signature. The Record TTL value is specified in minutes.

Signature Expiration and Signature Inception: Specify the validity period for the signature. The signature MUST NOT be used for authentication prior to the inception date and MUST NOT be used for authentication after the expiration date. Each field specifies a date and time in the form of a 32-bit unsigned number of seconds elapsed since 1 January 1970 00:00:00 UTC, ignoring leap seconds, in network byte order.

Key Tag: An identifier to specify which key is used for this signature if more than one valid key exists for the signing DDT node.

Sig Length: The length of the Signature field in bytes.

Sig-Algorithm: The identifier of the cryptographic algorithm used for the signature. Sig-Algorithm values defined in this specification are listed in Table 1. Implementations conforming to this specification MUST implement at least RSA-SHA256 for DDT signing. Sig-Algorithm type 1 (RSA-SHA1) is deprecated and SHOULD NOT be used.

Sig-Algorithm	Name	Reference	Notes
1	RSA-SHA1	[RFC8017]	DEPRECATED
2	RSA-SHA256	[RFC8017]	MANDATORY

Table 1: Sig-Algorithm Values

Reserved: MUST be set to 0 on transmit and MUST be ignored on receipt.

Signature: Contains the cryptographic signature that covers the entire Map-Referral Record to which this signature belongs. For the purpose of computing the signature, the Record TTL (Section 6.4) value is set to the value of Original Record TTL and the Signature field is filled with zeros.

7. DDT Network Elements and Their Operation

As described above, LISP-DDT introduces a new network element -- the DDT node -- and extends the functionality of Map-Servers and Map-Resolvers to send and receive Map-Referral messages. The operation of each of these devices is described below.

7.1. DDT Node

When a DDT node receives a DDT Map-Request, it compares the requested XEID against its list of XEID-prefix delegations and its list of authoritative XEID-prefixes, and proceeds as follows:

7.1.1. Matching of a Delegated Prefix (or Sub-prefix)

If the requested XEID matches one of the DDT node's delegated prefixes, then a Map-Referral message is returned with the matching more-specific XEID-prefix and the set of RLOCs for the referral target DDT nodes, including associated security information (see Section 10 for details on security). If at least one DDT node of the delegation is known to be a DDT Map-Server, then the Map-Referral message SHOULD be sent with action code MS-REFERRAL to indicate to the receiver that LISP-SEC information (if saved in the pending request) SHOULD be included in the next DDT Map-Request; otherwise, the action code NODE-REFERRAL SHOULD be used.

Note that a matched delegation does not have to be for a sub-prefix of an authoritative prefix; in addition to being configured to delegate sub-prefixes of an authoritative prefix, a DDT node may also be configured with other XEID-prefixes for which it can provide referrals to DDT nodes anywhere in the database hierarchy. This capability to define "shortcut hints" is never required to be configured, but it may be a useful heuristic for reducing the number of iterations needed to find an EID, particularly for private network deployments.

Referral hints, if used properly, may reduce the number of referrals a DDT client needs to follow to locate a DDT Map-Server authoritative for the XEID-prefix being resolved. On the other hand, the incorrect use of hints may create circular dependencies (or "referral loops") between DDT nodes. A DDT client MUST be prepared to handle such circular referrals. See Section 7.3.4 for a discussion of referral loops and measures that the DDT client must implement in order to detect circular referrals and prevent infinite looping.

Another danger related to the use of hints is when a DDT deployment spans multiple administrative domains (i.e., different authorities manage DDT nodes in the same DDT database). In this case, an

operator managing a DDT node may not be aware of the fact that the node is being referred to by hints. Locator addresses in hints may become stale when referred DDT nodes are taken out of service or change their locator addresses.

7.1.2. Missing Delegation from an Authoritative Prefix

If the requested XEID did not match a configured delegation but does match an authoritative XEID-prefix, then the DDT node MUST return a Negative Map-Referral that uses the least-specific XEID-prefix that does not match any XEID-prefix delegated by the DDT node. The action code is set to DELEGATION-HOLE; this indicates that the XEID is not a LISP destination.

If the requested XEID did not match either a configured delegation, an authoritative XEID-prefix, or a hint, then a Negative Map-Referral with action code NOT-AUTHORITATIVE MUST be returned.

7.2. DDT Map-Server

When a DDT Map-Server receives a DDT Map-Request, its operation is similar to that of a DDT node, with additional processing as follows:

- If the requested XEID matches a registered XEID-prefix, then the Map-Request is forwarded to one of the destination ETR RLOCs (or the Map-Server sends a Map-Reply, if it is providing a proxy Map-Reply service), and a Map-Referral with action code MS-ACK MUST be returned to the sender of the DDT Map-Request.

- If the requested XEID matches a configured XEID-prefix for which no ETR registration has been received, then a Negative Map-Referral with action code MS-NOT-REGISTERED MUST be returned to the sender of the DDT Map-Request.

7.3. DDT Client

A DDT client queries one or more DDT nodes and uses an iterative process of following returned referrals until it receives one with action code MS-ACK (or an error indication). MS-ACK indicates that the Map-Request has been sent to a Map-Server that will forward it to an ETR that, in turn, will provide a Map-Reply to the locator address in the Map-Request.

DDT client functionality will typically be implemented by DDT Map-Resolvers. Just as would any other Map-Resolver, a DDT Map-Resolver accepts Map-Requests from its clients (typically ITRs) and ensures that those Map-Requests are forwarded to the correct ETR, which generates Map-Replies. However, unlike a Map-Resolver that

uses the LISP Alternative Logical Topology (LISP+ALT) mapping system [RFC6836], a DDT Map-Resolver implements DDT client functionality to find the correct ETR to answer a Map-Request; this requires a DDT Map-Resolver to maintain additional state: a Map-Referral cache and a pending request list of XEIDs that are going through the iterative referral process.

DDT client functionality may be implemented on ITRs. In this case, the DDT client will not receive a Map-Request from another network element; instead, equivalent information will be provided to the DDT client via a programming interface.

7.3.1. Queuing and Sending DDT Map-Requests

When a DDT client receives a request to resolve an XEID (in the case of a DDT Map-Resolver, this will be in the form of a received Encapsulated Map-Request), it first performs a longest-match search for the XEID in its referral cache. If no match is found or if a negative cache entry is found, then the destination is not in the database; a Negative Map-Reply MUST be returned, and no further processing is performed by the DDT client.

If a match is found, the DDT client creates a pending request list entry for the XEID and saves the original request (in the case of a DDT Map-Resolver, this will be the original Map-Request minus the encapsulation header) along with other information needed to track progress through the iterative referral process; the "referral XEID-prefix" is also initialized to indicate that no referral has yet been received. The DDT client then creates a DDT Map-Request (which is an Encapsulated Map-Request with the "DDT-originated" flag set in the message header) for the XEID but without any authentication data that may have been included in the original request. It sends the DDT Map-Request to one of the RLOCs in the chosen referral cache entry. The referral cache is initially populated with one or more statically configured entries; additional entries are added when referrals are followed, as described below. A DDT client is not absolutely required to cache referrals, but doing so will decrease latency and reduce lookup delays.

Note that in normal use on the public Internet, the statically configured initial referral cache for a DDT client should include a "default" entry with RLOCs for either the root DDT node or one or more DDT nodes that contain hints for the root DDT node. If a DDT client does not have such a configuration, it will return a Negative Map-Reply if it receives a query for an EID outside the subset of the mapping database known to it. While this may be desirable on private network deployments or during early transition to LISP when few sites are using it, this behavior is not appropriate when LISP is in

general use on the Internet. If DDT message exchanges are authenticated as described in Section 10, then the DDT client MUST also be configured with public keys of DDT nodes pointed to by the "default" cache entry. In this case, the "default" entry will typically be for the root DDT node.

7.3.2. Receiving and Following Referrals

After sending a DDT Map-Request, a DDT client expects to receive a Map-Referral response. If none occurs within the timeout period, the DDT client retransmits the request, sending it to the next RLOC in the referral cache entry if one is available. If all RLOCs have been tried and the maximum number of retransmissions has occurred for each, then the pending request list entry is dequeued and discarded. In this case, the DDT client returns no response to the sender of the original request.

A DDT client processes a received Map-Referral message according to each action code:

NODE-REFERRAL: The DDT client checks for a possible referral loop as described in Section 7.3.4. If no loop is found, the DDT client saves the prefix returned in the Map-Referral message in the referral cache, updates the saved prefix and saved RLOCs in the pending request list entry, and follows the referral by sending a new DDT Map-Request to one of the DDT node RLOCs listed in the Referral Set; security information saved with the original Map-Request SHOULD NOT be included.

MS-REFERRAL: The DDT client processes an MS-REFERRAL in the same manner as a NODE-REFERRAL, except that security information saved with the original Map-Request MUST be included in the new Map-Request sent to a Map-Server (see Section 10 for details on security).

MS-ACK: An MS-ACK is returned by a DDT Map-Server to indicate that it has one or more registered ETRs that can answer a Map-Request for the XEID and the request has been forwarded to one of them (or, if the Map-Server is providing a proxy service for the prefix, then a reply has been sent to the querying ITR). If the pending request did not include saved LISP-SEC information or if that information was already included in the previous DDT Map-Request (sent by the DDT client in response to either an MS-REFERRAL or a previous MS-ACK referral), then the pending request for the XEID is complete; processing of the request stops, and all request state can be discarded. Otherwise, LISP-SEC information is required and has not yet been sent to the authoritative DDT Map-Server; the DDT client MUST resend the DDT

Map-Request with LISP-SEC information included, and the pending request queue entry remains until another Map-Referral with action code MS-ACK is received. If the "Incomplete" flag is not set, the prefix is saved in the referral cache.

MS-NOT-REGISTERED: The DDT Map-Server queried could not process the request because it did not have any ETRs registered for a matching, authoritative XEID-prefix. If the DDT client has not yet tried all of the RLOCs saved with the pending request, then it sends a Map-Request to the next RLOC in that list. If all RLOCs have been tried, then the destination XEID is not registered and is unreachable. The DDT client MUST return a Negative Map-Reply to the requester (or, in the case of a DDT Map-Resolver, to the sender of the original Map-Request). This Map-Reply contains the least-specific XEID-prefix in the range for which this DDT Map-Server is authoritative and in which no registrations exist. The TTL value of the Negative Map-Reply SHOULD be set to 1 minute. A negative referral cache entry is created for the prefix (whose TTL also SHOULD be set to 1 minute), and processing of the request stops.

DELEGATION-HOLE: The DDT Map-Server queried did not have an XEID-prefix defined that matched the requested XEID, so the XEID does not exist in the mapping database. The DDT client MUST return a Negative Map-Reply to the requester (or, in the case of a DDT Map-Resolver, to the sender of the original Map-Request); this Map-Reply SHOULD indicate the least-specific XEID-prefix matching the requested XEID for which no delegations exist and SHOULD have a TTL value of 15 minutes. A negative referral cache entry is created for the prefix (which also SHOULD have a TTL of 15 minutes), and processing of the pending request stops.

NOT-AUTHORITATIVE: The DDT Map-Server queried is not authoritative for the requested XEID. This can occur if a cached referral has become invalid due to a change in the database hierarchy. If the DDT client receiving this message can determine that it is using old cached information, it MAY choose to delete that cached information and retry the original Map-Request, starting from its "root" cache entry. If this action code is received in response to a query that did not use cached referral information, then it indicates a database synchronization problem or configuration error. The pending request is silently discarded; i.e., all state for the request that caused this answer is removed, and no answer is returned to the original requester.

7.3.3. Handling Referral Errors

Other states are possible, such as a misconfigured DDT node (acting as a proxy Map-Server, for example) returning a Map-Reply to the DDT client; they should be considered errors and logged as such. It is not clear exactly what else the DDT client should do in such cases; one possibility is to remove the pending request list entry and send a Negative Map-Reply to the requester (or, in the case of a DDT Map-Resolver, to the sender of the original Map-Request). Alternatively, if a DDT client detects unexpected behavior by a DDT node, it could mark that node as unusable in its referral cache and update the pending request to try a different DDT node if more than one is listed in the referral cache. In any case, any prefix contained in a Map-Referral message that causes a referral error (including a referral loop) is not saved in the DDT client referral cache.

7.3.4. Referral Loop Detection

In response to a Map-Referral message with action code NODE-REFERRAL or MS-REFERRAL, a DDT client is directed to query a new set of DDT node RLOCs that are expected to have more-specific XEID-prefix information for the requested XEID. To prevent a possible "iteration loop" (following referrals back and forth among a set of DDT nodes without ever finding an answer), a DDT client saves the last received referral XEID-prefix for each pending request and checks to see if a newly received NODE-REFERRAL or MS-REFERRAL message contains a more-specific referral XEID-prefix; an exact or less-specific match of the saved XEID-prefix indicates a referral loop. If a loop is detected, the DDT Map-Resolver handles the request as described in Section 7.3.3. Otherwise, the DDT client saves the most recently received referral XEID-prefix with the pending request when it follows the referral.

As an extra measure to prevent referral loops, it is probably also wise to limit the total number of referrals for any request to some reasonable number; the exact value of that number will be determined during experimental deployment of LISP-DDT but is bounded by the maximum length of the XEID.

Note that when a DDT client adds an entry to its lookup queue and sends an initial Map-Request for an XEID, the queue entry has no previous referral XEID-prefix; this means that the first DDT node contacted by a DDT Map-Resolver may provide a referral to anywhere in the DDT hierarchy. This, in turn, allows a DDT client to use essentially any DDT node RLOCs for its initial cache entries and

depend on the initial referral to provide a good starting point for Map-Requests; there is no need to configure the same set of root DDT nodes on all DDT clients.

8. Pseudocode and Decision Tree Diagrams

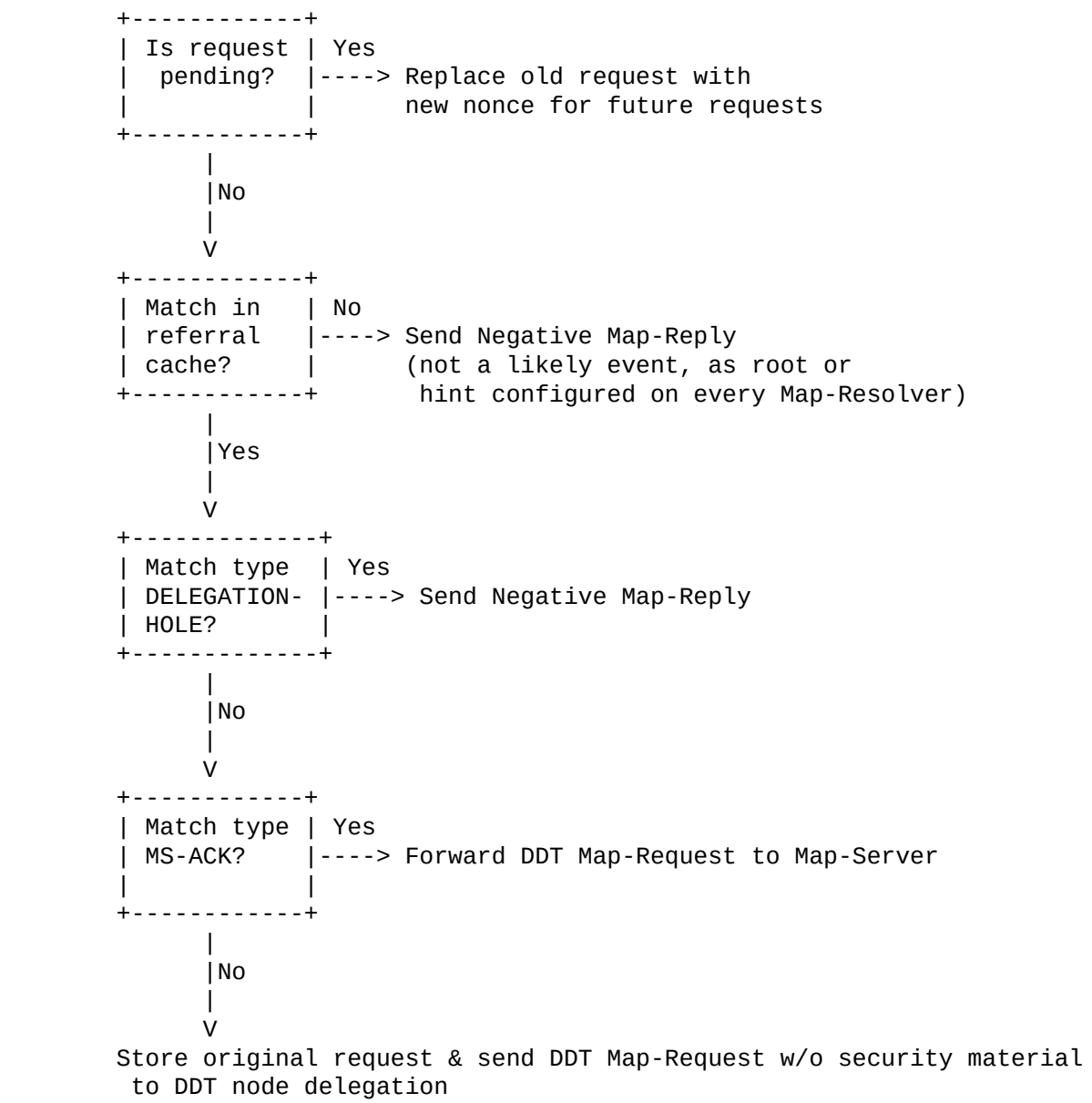
To illustrate the DDT algorithms described above and to aid in implementation, each of the major DDT Map-Server and DDT Map-Resolver functions are described below, first using simple "pseudocode" and then in the form of a decision tree.

8.1. Map-Resolver Processing of ITR Map-Request

8.1.1. Pseudocode Summary

```
if ( request pending, i.e., (ITR,EID) of request same ) {
    replace old request with new, & use new request nonce
     for future requests
} else if ( no match in refcache ) {
    return Negative Map-Reply to ITR
} else if ( match type DELEGATION-HOLE ) {
    return Negative Map-Reply to ITR
} else if ( match type MS-ACK ) {
    fwd DDT Map-Request to Map-Server
} else {
    store & fwd DDT Map-Request w/o security material
     to node delegation
}
```

8.1.2. Decision Tree Diagram



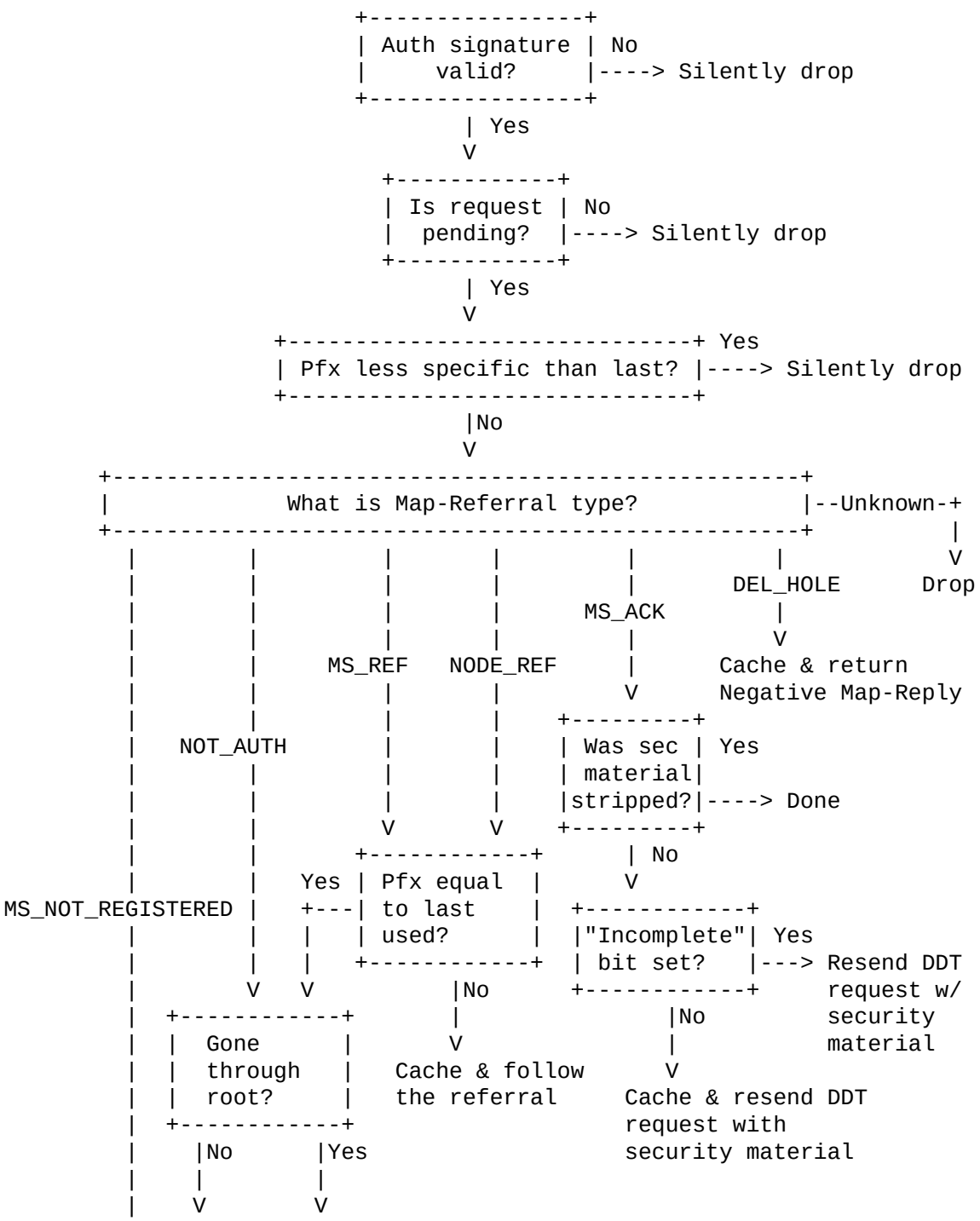
8.2. Map-Resolver Processing of Map-Referral Message

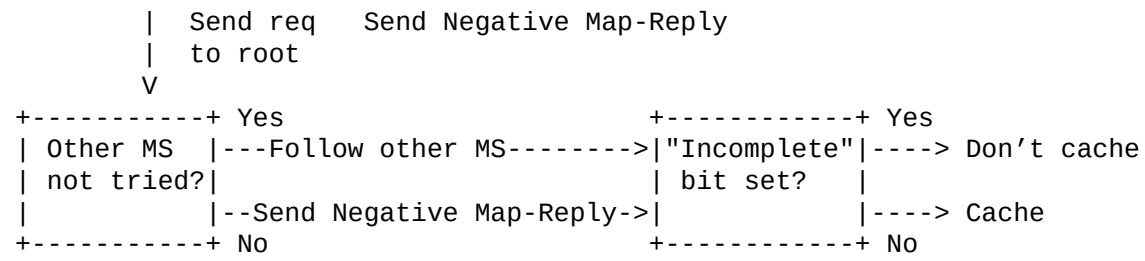
8.2.1. Pseudocode Summary

```
if ( authentication signature validation failed ) {
    silently drop
}

if ( no request pending matched by referral nonce ) {
    silently drop
}

if ( pfx in referral less specific than last referral used ) {
    if ( gone through root ) {
        silently drop
    } else {
        send request to root
    }
}

switch (map_referral_type) {

    case NOT_AUTHORITATIVE:
        if ( gone through root ) {
            return Negative Map-Reply to ITR
        } else {
            send request to root
        }

    case DELEGATION_HOLE:
        cache & send Negative Map-Reply to ITR

    case MS_REFERRAL:
        if ( referral equal to last used ) {
            if ( gone through root ) {
                return Negative Map-Reply to ITR
            } else {
                send request to root
            }
        } else {
            cache
            follow the referral; include security material
        }
```

```
        case NODE_REFERRAL:
            if ( referral equal to last used ) {
                if ( gone through root ) {
                    return Negative Map-Reply to ITR
                } else {
                    send request to root
                }
            } else {
                cache
                follow the referral; strip security material
            }

        case MS_ACK:
            if ( security material stripped ) {
                resend request with security material
                if { !incomplete } {
                    cache
                }
            }

        case MS_NOT_REGISTERED:
            if { all Map-Server delegations not tried } {
                follow delegations not tried
                if ( !incomplete ) {
                    cache
                }
            } else {
                send Negative Map-Reply to ITR
                if { !incomplete } {
                    cache
                }
            }

        case DEFAULT:
            drop
        }
    }
```

8.2.2. Decision Tree Diagram





8.3. DDT Node Processing of DDT Map-Request Message

8.3.1. Pseudocode Summary

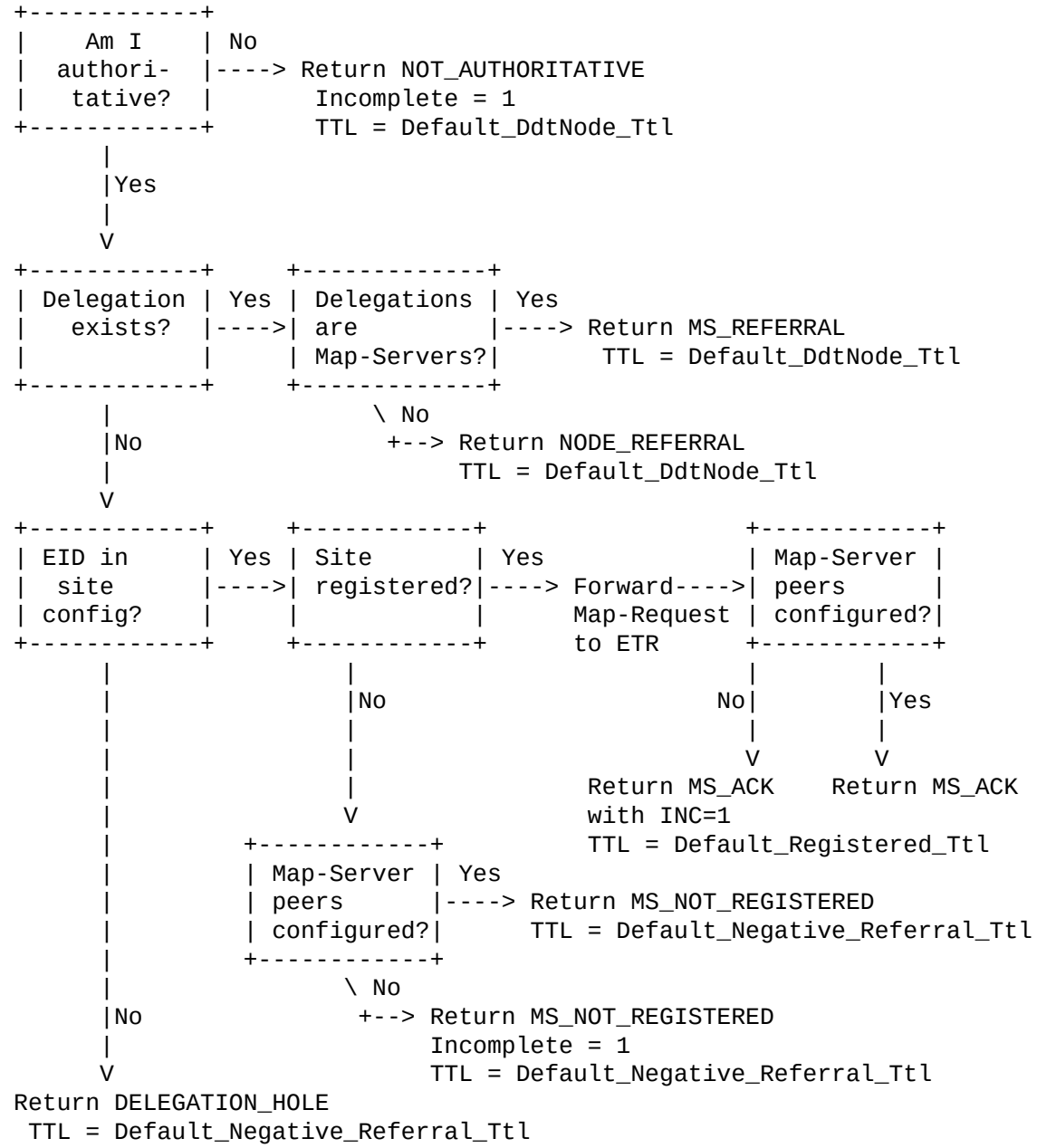
```
  if ( I am not authoritative ) {
      send Map-Referral NOT_AUTHORITATIVE with
       "Incomplete" bit set and TTL 0
  } else if ( delegation exists ) {
      if ( delegated Map-Servers ) {
          send Map-Referral MS_REFERRAL with
            TTL 'Default_DdtNode_Ttl'
      } else {
          send Map-Referral NODE_REFERRAL with
            TTL 'Default_DdtNode_Ttl'
      }
  } else {
      if ( EID in site) {
          if ( site registered ) {
              forward Map-Request to ETR
              if ( Map-Server peers configured ) {
                  send Map-Referral MS_ACK with
                   TTL 'Default_Registered_Ttl'
              } else {
                  send Map-Referral MS_ACK with
                   TTL 'Default_Registered_Ttl' and "Incomplete" bit set
              }
          } else {
              if ( Map-Server peers configured ) {
                  send Map-Referral MS_NOT_REGISTERED with
                   TTL 'Default_Configured_Not_Registered_Ttl'
              } else {
                  send Map-Referral MS_NOT_REGISTERED with
                   TTL 'Default_Configured_Not_Registered_Ttl'
                   and "Incomplete" bit set
              }
          }
```

```
      } else {
          send Map-Referral DELEGATION_HOLE with
           TTL 'Default_Negative_Referral_Ttl'
      }
  }
```

where architectural constants for TTL are set as follows:

Default_DdtNode_Ttl	1440 minutes
Default_Registered_Ttl	1440 minutes
Default_Negative_Referral_Ttl	15 minutes
Default_Configured_Not_Registered_Ttl	1 minute

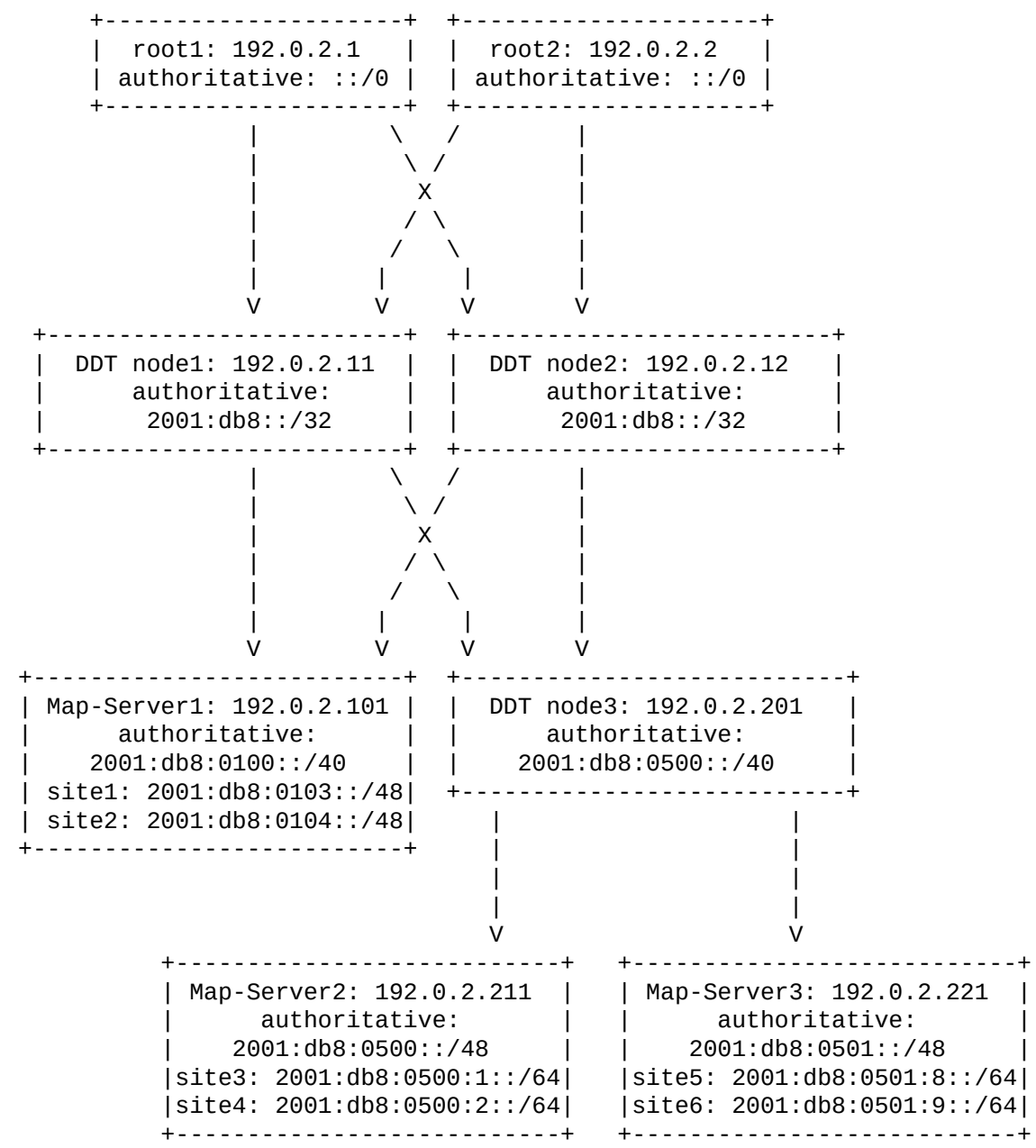
8.3.2. Decision Tree Diagram



9. Example Topology and Request/Referral Following

This section shows an example DDT tree and several possible scenarios of Map-Requests coming to a Map-Resolver and subsequent iterative DDT referrals. In this example, RLOCs of DDT nodes are shown in the IPv4 address space while the EIDs are in the IPv6 AF. The same principle of hierarchical delegation and pinpointing referrals is equally applicable to any AF whose address hierarchy can be expressed as a bit string with associated length. The DDT "tree" of IPv4 prefixes is another AF with immediate practical value. This section could benefit from additional examples, perhaps including one using IPv4 EIDs and another using IPv6 RLOCs. If this document is moved to the Standards Track, consideration should be given to adding such examples.

To show how referrals are followed to find the RLOCs for a number of EIDs, consider the following example EID topology for DBID=0, IID=0, AFI=2, and EID=0/0:



DDT nodes are configured for this "root" at IP addresses 192.0.2.1 and 192.0.2.2. DDT Map-Resolvers are configured with default referral cache entries for these addresses.

The root DDT nodes delegate 2001:db8::/32 to two DDT nodes with IP addresses 192.0.2.11 and 192.0.2.12.

The DDT nodes for 2001:db8::/32 delegate 2001:db8:0100::/40 to a DDT Map-Server with RLOC 192.0.2.101.

The DDT Map-Server for 2001:db8:0100::/40 is configured to allow ETRs to register the sub-prefixes 2001:db8:0103::/48 and 2001:db8:0104::/48.

The DDT nodes for 2001:db8::/32 also delegate 2001:db8:0500::/40 to a DDT node with RLOC 192.0.2.201.

The DDT node for 2001:db8:0500::/40 is further configured to delegate 2001:db8:0500::/48 to a DDT Map-Server with RLOC 192.0.2.211 and 2001:db8:0501::/48 to a DDT Map-Server with RLOC 192.0.2.221.

The DDT Map-Server for 2001:db8:0500::/48 is configured to allow ETRs to register the sub-prefixes 2001:db8:0500:1::/64 and 2001:db8:0500:2::/64.

The DDT Map-Server for 2001:db8:0501::/48 is configured to allow ETRs to register the sub-prefixes 2001:db8:0501:8::/64 and 2001:db8:0501:9::/64.

9.1. Lookup of 2001:db8:0103:1::1/128

The first example shows a DDT Map-Resolver following a delegation from the root to a DDT node followed by another delegation to a DDT Map-Server.

ITR1 sends an Encapsulated Map-Request for 2001:db8:0103:1::1 to one of its configured (DDT) Map-Resolvers. The DDT Map-Resolver proceeds as follows:

1. Send a DDT Map-Request (for 2001:db8:0103:1::1) to one of the root DDT nodes (192.0.2.1 or 192.0.2.2).

2. Receive (and save in the referral cache) the Map-Referral for EID-prefix 2001:db8::/32, action code NODE-REFERRAL, RLOC set (192.0.2.11, 192.0.2.12).

3. Send a DDT Map-Request to 192.0.2.11 or 192.0.2.12.

4. Receive (and save in the referral cache) the Map-Referral for EID-prefix 2001:db8:0100::/40, action code MS-REFERRAL, RLOC set (192.0.2.101).

5. Send a DDT Map-Request to 192.0.2.101; if the ITR-originated Encapsulated Map-Request had a LISP-SEC signature, it is included.

6. The DDT Map-Server at 192.0.2.101 decapsulates the DDT Map-Request and forwards the Map-Request to a registered site1 ETR for 2001:db8:0103::/48.

7. The DDT Map-Server at 192.0.2.101 sends a Map-Referral message for EID-prefix 2001:db8:0103::/48, action code MS-ACK, to the DDT Map-Resolver.

8. The DDT Map-Resolver receives the Map-Referral message and dequeues the pending request for 2001:db8:0103:1::1.

9. The site1 ETR for 2001:db8:0103::/48 receives the Map-Request forwarded by the DDT Map-Server and sends a Map-Reply to ITR1.

9.2. Lookup of 2001:db8:0501:8:4::1/128

The next example shows a three-level delegation: root to first DDT node, first DDT node to second DDT node, and second DDT node to DDT Map-Server.

ITR2 sends an Encapsulated Map-Request for 2001:db8:0501:8:4::1 to one of its configured (DDT) Map-Resolvers, which are different from those for ITR1. The DDT Map-Resolver proceeds as follows:

1. Send a DDT Map-Request (for 2001:db8:0501:8:4::1) to one of the root DDT nodes (192.0.2.1 or 192.0.2.2).

2. Receive (and save in the referral cache) the Map-Referral for EID-prefix 2001:db8::/32, action code NODE-REFERRAL, RLOC set (192.0.2.11, 192.0.2.12).

3. Send a DDT Map-Request to 192.0.2.11 or 192.0.2.12.

4. Receive (and save in the referral cache) the Map-Referral for EID-prefix 2001:db8:0500::/40, action code NODE-REFERRAL, RLOC set (192.0.2.201).

5. Send a DDT Map-Request to 192.0.2.201.

6. Receive (and save in the referral cache) the Map-Referral for EID-prefix 2001:db8:0501::/48, action code MS-REFERRAL, RLOC set (192.0.2.221).

7. Send a DDT Map-Request to 192.0.2.221; if the ITR-originated Encapsulated Map-Request had a LISP-SEC signature, it is included.

8. The DDT Map-Server at 192.0.2.221 decapsulates the DDT Map-Request and forwards the Map-Request to a registered site5 ETR for 2001:db8:0501:8::/64.

9. The DDT Map-Server at 192.0.2.221 sends a Map-Referral message for EID-prefix 2001:db8:0501:8::/64, action code MS-ACK, to the DDT Map-Resolver.

10. The DDT Map-Resolver receives a Map-Referral(MS-ACK) message and dequeues the pending request for 2001:db8:0501:8:4::1.

11. The site5 ETR for 2001:db8:0501:8::/64 receives a Map-Request forwarded by the DDT Map-Server and sends a Map-Reply to ITR2.

9.3. Lookup of 2001:db8:0104:2::2/128

This example shows how a DDT Map-Resolver uses a saved referral cache entry to skip the referral process and go directly to a DDT Map-Server for a prefix that is similar to one previously requested.

In this case, ITR1 uses the same Map-Resolver used in the example in Section 9.1. It sends an Encapsulated Map-Request for 2001:db8:0104:2::2 to that (DDT) Map-Resolver. The DDT Map-Resolver finds an MS-REFERRAL cache entry for 2001:db8:0100::/40 with RLOC set (192.0.2.101) and proceeds as follows:

1. Send a DDT Map-Request (for 2001:db8:0104:2::2) to 192.0.2.101; if the ITR-originated Encapsulated Map-Request had a LISP-SEC signature, it is included.

2. The DDT Map-Server at 192.0.2.101 decapsulates the DDT Map-Request and forwards the Map-Request to a registered site2 ETR for 2001:db8:0104::/48.

3. The DDT Map-Server at 192.0.2.101 sends a Map-Referral message for EID-prefix 2001:db8:0104::/48, action code MS-ACK, to the DDT Map-Resolver.

4. The DDT Map-Resolver receives the Map-Referral (MS-ACK) and dequeues the pending request for 2001:db8:0104:2::2.

5. The site2 ETR for 2001:db8:0104::/48 receives a Map-Request and sends a Map-Reply to ITR1.

9.4. Lookup of 2001:db8:0500:2:4::1/128

This example shows how a DDT Map-Resolver uses a saved referral cache entry to start the referral process at a non-root, intermediate DDT node for a prefix that is similar to one previously requested.

In this case, ITR2 uses the same Map-Resolver used in the example in Section 9.2. It sends an Encapsulated Map-Request for 2001:db8:0500:2:4::1 to that (DDT) Map-Resolver, which finds a NODE-REFERRAL cache entry for 2001:db8:0500::/40 with RLOC set (192.0.2.201). It proceeds as follows:

1. Send a DDT Map-Request (for 2001:db8:0500:2:4::1) to 192.0.2.201.

2. Receive (and save in the referral cache) the Map-Referral for EID-prefix 2001:db8:0500::/48, action code MS-REFERRAL, RLOC set (192.0.2.211).

3. Send a DDT Map-Request to 192.0.2.211; if the ITR-originated Encapsulated Map-Request had a LISP-SEC signature, it is included.

4. The DDT Map-Server at 192.0.2.211 decapsulates the DDT Map-Request and forwards the Map-Request to a registered site4 ETR for 2001:db8:0500:2::/64.

5. The DDT Map-Server at 192.0.2.211 sends a Map-Referral message for EID-prefix 2001:db8:0500:2::/64, action code MS-ACK, to the DDT Map-Resolver.

6. The DDT Map-Resolver receives the Map-Referral (MS-ACK) and dequeues the pending request for 2001:db8:0500:2:4::1.

7. The site4 ETR for 2001:db8:0500:2::/64 receives a Map-Request and sends a Map-Reply to ITR2.

9.5. Lookup of 2001:db8:0500::1/128 (Nonexistent EID)

This example uses the cached MS-REFERRAL for 2001:db8:0500::/48 learned above to start the lookup process at the DDT Map-Server at 192.0.2.211. The DDT Map-Resolver proceeds as follows:

1. Send a DDT Map-Request (for 2001:db8:0500::1) to 192.0.2.211; if the ITR-originated Encapsulated Map-Request had a LISP-SEC signature, it is included.

2. The DDT Map-Server at 192.0.2.211, which is authoritative for 2001:db8:0500::/48, does not have a matching delegation for 2001:db8:0500::1. It responds with a Map-Referral message for 2001:db8:0500::/64, action code DELEGATION-HOLE, to the DDT Map-Resolver. The prefix 2001:db8:0500::/64 is used because it is the least-specific prefix that does match the requested EID but does not match one of the configured delegations (2001:db8:0500:1::/64 and 2001:db8:0500:2::/64).

3. The DDT Map-Resolver receives the delegation, adds a negative referral cache entry for 2001:db8:0500::/64, dequeues the pending request for 2001:db8:0500::1, and returns a Negative Map-Reply to ITR2.

10. Securing the Database and Message Exchanges

This section specifies the DDT security architecture that provides data origin authentication, data integrity protection, and XEID-prefix delegation. Global XEID-prefix authorization is out of scope for this document.

Each DDT node is configured with one or more public/private key pairs that are used to digitally sign Map-Referral Records for XEID-prefix(es) for which the DDT node is authoritative. In other words, each public/private key pair is associated with the combination of a DDT node and an XEID-prefix for which it is authoritative. Every DDT node is also configured with the public keys of its child DDT nodes. By including the public keys of target child DDT nodes in the Map-Referral Records and signing each Record with the DDT node's private key, a DDT node can securely delegate sub-prefixes of its authoritative XEID-prefixes to its child DDT nodes. A DDT node configured to provide hints must also have the public keys of the DDT nodes to which its hints point. DDT node keys can be encoded using LCAF Type 11 to associate the key to the RLOC of the referred DDT node. If a node has more than one public key, it should sign its Records with at least one of these keys. When a node has N keys, it can sustain up to N-1 key compromises. The revocation mechanism is described in Section 10.2.1.

Map-Resolvers are configured with one or more trusted public keys, referred to as "trust anchors". Trust anchors are used to authenticate the DDT security infrastructure. Map-Resolvers can discover a DDT node's public key by either (1) having it configured as a trust anchor or (2) obtaining it from the node's parent as part of a signed Map-Referral. When a public key is obtained from a node's parent, it is considered trusted if it is signed by a trust anchor or if it is signed by a key that was previously trusted. Typically, in a Map-Resolver, the root DDT node's public keys should be configured as trust anchors. Once a Map-Resolver authenticates a public key, it locally caches the key along with the associated DDT node RLOC and XEID-prefix for future use.

10.1. XEID-Prefix Delegation

In order to delegate XEID sub-prefixes to its child DDT nodes, a parent DDT node signs its Map-Referrals. Every signed Map-Referral MUST also include the public keys associated with each child DDT node. Such a signature indicates that the parent DDT node is delegating the specified XEID-prefix to a given child DDT node. The signature is also authenticating the public keys associated with the child DDT nodes, and authorizing them to be used by the child DDT nodes, to provide origin authentication and integrity protection for further delegations and mapping information of the XEID-prefix allocated to the DDT node.

As a result, for a given XEID-prefix, a Map-Resolver can form an authentication chain from a configured trust anchor (typically the root DDT node) to the leaf nodes (Map-Servers). Map-Resolvers leverage this authentication chain to verify the Map-Referral signatures while walking the DDT tree until they reach a Map-Server authoritative for the given XEID-prefix.

10.2. DDT Node Operation

Upon receiving a Map-Request, the DDT node responds with a Map-Referral as specified in Section 7. For every Record present in the Map-Referral, the DDT node also includes the public keys associated with the Record's XEID-prefix and the RLOCs of the child DDT nodes. Each Record contained in the Map-Referral is signed using the DDT node's private key.

10.2.1. DDT Public Key Revocation

The node that owns a public key can also revoke that public key. For instance, if a parent DDT node advertises a public key for one of its child DDT nodes, the child DDT node can at a later time revoke that key. Since DDT nodes do not keep track of the Map-Resolvers that

query them, revocation is done in a pull model, where the Map-Resolver is informed of the revocation of a key only when it queries the node that owns that key. If the parent DDT node is configured to advertise that key, the parent DDT node must also be signaled to remove the key from the Records it advertises for the child DDT node; this is necessary to avoid further distribution of the revoked key.

To securely revoke a key, the DDT node creates a new Record for the associated XEID-prefix and locator, including the revoked key with the R bit set. (See Section 4.7 of [RFC8060] for details regarding the R bit.) The DDT node must also include a signature in the Record that covers this Record; this is computed using the private key corresponding to the key being revoked. Such a Record is termed a "revocation record". By including this Record in its Map-Referrals, the DDT node informs querying Map-Resolvers about the revoked key. A digital signature computed with a revoked key can only be used to authenticate the revocation and SHOULD NOT be used to validate any data. To prevent a compromised key from revoking other valid keys, a given key can only be used to sign a revocation for that specific key; it cannot be used to revoke other keys. This prevents the use of a compromised key to revoke other valid keys as described in [RFC5011]. A revocation record MUST be advertised for a period of time equal to or greater than the TTL value of the Record that initially advertised the key, starting from the time that the advertisement of the key was stopped by removal from the parent DDT node.

10.3. Map-Server Operation

Similar to a DDT node, a Map-Server is configured with one or more public/private key pairs that it must use to sign Map-Referrals.

However, unlike DDT nodes, Map-Servers do not delegate prefixes and as a result do not need to include keys in the Map-Referrals they generate.

10.4. Map-Resolver Operation

Upon receiving a Map-Referral, the Map-Resolver MUST first verify the signature(s) by using either a trust anchor or a previously authenticated public key associated with the DDT node sending the Map-Referral. If multiple authenticated keys are associated with the DDT node sending this Map-Referral, the Key Tag field (Section 6.4.1) of the signature can be used to select the correct public key for verifying the signature. If the key tag matches more than one key associated with that DDT node, the Map-Resolver MUST try to verify the signature with all matching keys. For every matching key that is

found, the Map-Resolver MUST also verify that the key is authoritative for the XEID-prefix in the Map-Referral Record. If such a key is found, the Map-Resolver MUST use it to verify the associated signature in the Record. If (1) no matching key is found, (2) none of the matching keys is authoritative for the XEID-prefix in the Map-Referral Record, or (3) such a key is found but the signature is not valid, the Map-Referral Record is considered corrupted and MUST be discarded. This may be due to expired keys. The Map-Resolver MAY try other siblings of this node if there is an alternate node that is authoritative for the same prefix. If not, the Map-Resolver CAN query the DDT node's parent to retrieve a valid key. It is good practice to use a counter or timer to avoid repeating this process if the Map-Resolver cannot verify the signature after several attempts.

Once the signature is verified, the Map-Resolver has verified the XEID-prefix delegation in the Map-Referral. This also means that public keys of the child DDT nodes were authenticated; the Map-Resolver must add these keys to the authenticated keys associated with each child DDT node and XEID-prefix. These keys are considered valid for the duration specified in the Record's TTL field.

11. Open Issues and Considerations

There are a number of issues with the organization of the mapping database that need further investigation. Among these are:

- Defining an interface to implement interconnection and/or interoperability with other mapping databases, such as LISP+ALT.

- Additional key structures for use with LISP-DDT, such as key structures to support additional EID formats as defined in [RFC8060].

- Management of the DDT Map-Resolver referral cache -- in particular, detecting and removing outdated entries.

- Best practices for either configuring hint referrals or avoiding their use.

Operational experience will help answer open questions surrounding these and other issues.

12. IANA Considerations

IANA has made the following early assignment per this document:

- Message type 6, "LISP DDT Map-Referral", was added to the "LISP Packet Types" registry. See Section 6.4 ("Map-Referral Message Format").

As this document is an Experimental RFC, this is an early allocation as per [RFC7120].

13. Security Considerations

Section 10 describes a DDT security architecture that provides data origin authentication, data integrity protection, and XEID-prefix delegation within the DDT infrastructure.

Global XEID-prefix authorization is beyond the scope of this document, but the Secure Inter-Domain Routing (SIDR) working group [RFC6480] is developing an infrastructure to support improved security of Internet routing. Further work is required to determine if SIDR's Public Key Infrastructure (PKI) and the distributed repository system it uses for storing and disseminating PKI data objects may also be used by DDT devices to verifiably assert that they are the legitimate holders of a set of XEID-prefixes.

This document specifies how DDT security and LISP-SEC [LISP-SEC] complement one another to secure the DDT infrastructure, Map-Referral messages, and the Map-Request/Map-Reply protocols. In the future, other LISP security mechanisms may be developed to replace LISP-SEC. Such future security mechanisms should describe how they can be used together with LISP-DDT to provide similar levels of protection.

LISP-SEC can use the DDT public-key infrastructure to secure the transport of LISP-SEC key material (the One-Time Key) from a Map-Resolver to the corresponding Map-Server. For this reason, when LISP-SEC is deployed in conjunction with a LISP-DDT mapping database and the path between the Map-Resolver and Map-Server needs to be protected, DDT security as described in Section 10 should be enabled as well.

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Authors' Addresses

Vince Fuller
VAF.NET Internet Consulting

Email: vince.fuller@gmail.com

Darrel Lewis
Cisco Systems

Email: darlewis@cisco.com

Vina Ermagan
Cisco Systems

Email: vermagan@cisco.com

Amit Jain
Juniper Networks

Email: atjain@juniper.net

Anton Smirnov
Cisco Systems

Email: as@cisco.com