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REsource LOcation And Discovery (RELOAD) Base Protocol

Abstract

This specification defines REsource LOcation And Discovery (RELOAD), a peer-to-peer (P2P) signaling protocol for use on the Internet. A P2P signaling protocol provides its clients with an abstract storage and messaging service between a set of cooperating peers that form the overlay network. RELOAD is designed to support a P2P Session Initiation Protocol (P2PSIP) network, but can be utilized by other applications with similar requirements by defining new usages that specify the Kinds of data that need to be stored for a particular application. RELOAD defines a security model based on a certificate enrollment service that provides unique identities. NAT traversal is a fundamental service of the protocol. RELOAD also allows access from "client" nodes that do not need to route traffic or store data for others.

Status of This Memo

This is an Internet Standards Track document.

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). Further information on Internet Standards is available in Section 2 of RFC 5741.

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/rfc6940.

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1. Introduction

This document defines REsource LOcation And Discovery (RELOAD), a peer-to-peer (P2P) signaling protocol for use on the Internet. RELOAD provides a generic, self-organizing overlay network service, allowing nodes to route messages to other nodes and to store and retrieve data in the overlay. RELOAD provides several features that are critical for a successful P2P protocol for the Internet:

Security Framework: A P2P network will often be established among a set of peers that do not trust each other. RELOAD leverages a central enrollment server to provide credentials for each peer, which can then be used to authenticate each operation. This greatly reduces the possible attack surface.

Usage Model: RELOAD is designed to support a variety of applications, including P2P multimedia communications with the Session Initiation Protocol (SIP) [SIP-RELOAD]. RELOAD allows the definition of new application usages, each of which can define its own data types, along with the rules for their use. This allows RELOAD to be used with new applications through a simple documentation process that supplies the details for each application.

NAT Traversal: RELOAD is designed to function in environments where many, if not most, of the nodes are behind NATs or firewalls. Operations for NAT traversal are part of the base design, including using Interactive Connectivity Establishment (ICE) [RFC5245] to establish new RELOAD or application protocol connections.

Optimized Routing: The very nature of overlay algorithms introduces a requirement that peers participating in the P2P network route requests on behalf of other peers in the network. This introduces a load on those other peers in the form of bandwidth and processing power. RELOAD has been defined with a simple, lightweight forwarding header, thus minimizing the amount of effort for intermediate peers.

Pluggable Overlay Algorithms: RELOAD has been designed with an abstract interface to the overlay layer to simplify implementing a variety of structured (e.g., distributed hash tables (DHTs)) and unstructured overlay algorithms. The idea here is that RELOAD provides a generic structure that can fit most types of overlay topologies (ring, hyperspace, etc.). To instantiate an actual network, you combine RELOAD with a specific overlay algorithm, which defines how to construct the overlay topology and route messages efficiently within it. This specification also defines

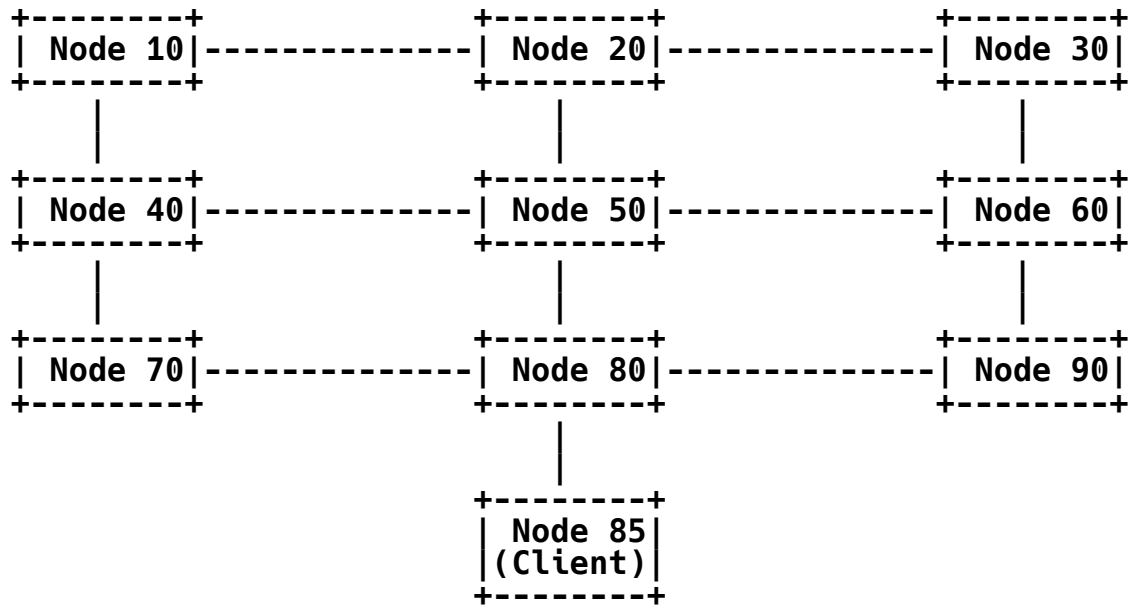
how RELOAD is used with the Chord-based [Chord] DHT algorithm, which is mandatory to implement. Specifying a default "mandatory-to-implement" overlay algorithm promotes interoperability, while extensibility allows selection of overlay algorithms optimized for a particular application.

Support for Clients: RELOAD clients differ from RELOAD peers primarily in that they do not store information on behalf of other nodes in the overlay. Rather, they use the overlay only to locate users and resources, as well as to store information and to contact other nodes.

These properties were designed specifically to meet the requirements for a P2P protocol to support SIP. This document defines the base protocol for the distributed storage and location service, as well as critical usage for NAT traversal. The SIP Usage itself is described separately in [SIP-RELOAD]. RELOAD is not limited to usage by SIP and could serve as a tool for supporting other P2P applications with similar needs.

1.1. Basic Setting

In this section, we provide a brief overview of the operational setting for RELOAD. A RELOAD Overlay Instance consists of a set of nodes arranged in a partly connected graph. Each node in the overlay is assigned a numeric Node-ID for the lifetime of the node, which, together with the specific overlay algorithm in use, determines its position in the graph and the set of nodes it connects to. The Node-ID is also tightly coupled to the certificate (see Section 13.3). The figure below shows a trivial example which isn't drawn from any particular overlay algorithm, but was chosen for convenience of representation.



Because the graph is not fully connected, when a node wants to send a message to another node, it may need to route it through the network. For instance, Node 10 can talk directly to nodes 20 and 40, but not to Node 70. In order to send a message to Node 70, it would first send it to Node 40, with instructions to pass it along to Node 70. Different overlay algorithms will have different connectivity graphs, but the general idea behind all of them is to allow any node in the graph to efficiently reach every other node within a small number of hops.

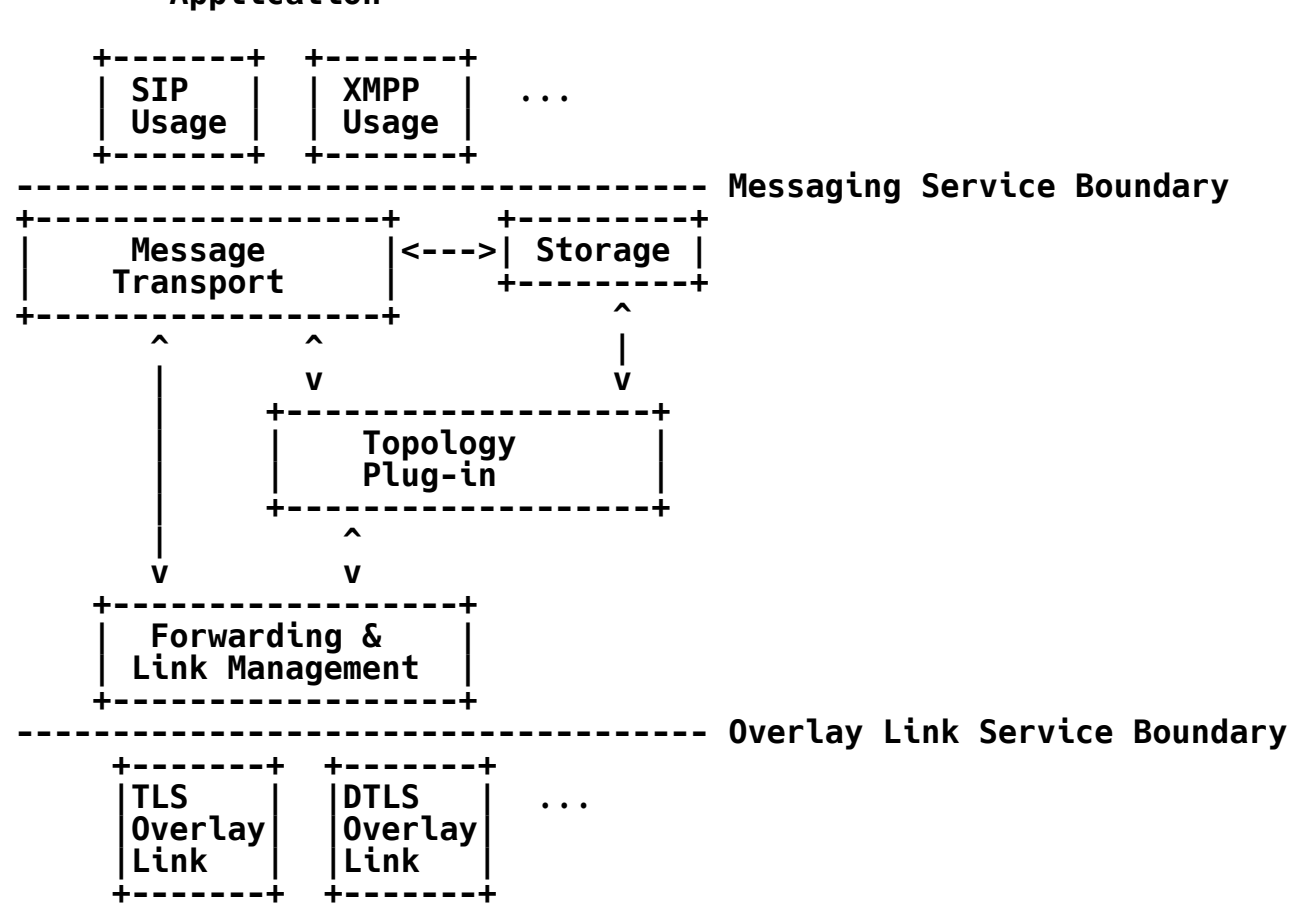
The RELOAD network is not only a messaging network. It is also a storage network, albeit one designed for small-scale transient storage rather than for bulk storage of large objects. Records are stored under numeric addresses, called Resource-IDs, which occupy the same space as node identifiers. Peers are responsible for storing the data associated with some set of addresses, as determined by their Node-ID. For instance, we might say that every peer is responsible for storing any data value which has an address less than or equal to its own Node-ID, but greater than the next lowest Node-ID. Thus, Node 20 would be responsible for storing values 11-20.

RELOAD also supports clients. These are nodes which have Node-IDs but do not participate in routing or storage. For instance, in the figure above, Node 85 is a client. It can route to the rest of the RELOAD network via Node 80, but no other node will route through it, and Node 90 is still responsible for addresses in the range [81..90]. We refer to non-client nodes as peers.

Other applications (for instance, SIP) can be defined on top of RELOAD and can use these two basic RELOAD services to provide their own services.

1.2. Architecture

RELOAD is fundamentally an overlay network. The following figure shows the layered RELOAD architecture.



The major components of RELOAD are:

Usage Layer: Each application defines a RELOAD Usage, which is a set of data Kinds and behaviors which describe how to use the services provided by RELOAD. These usages all talk to RELOAD through a common Message Transport Service.

Message Transport: Handles end-to-end reliability, manages request state for the usages, and forwards Store and Fetch operations to the Storage component. It delivers message responses to the component initiating the request.

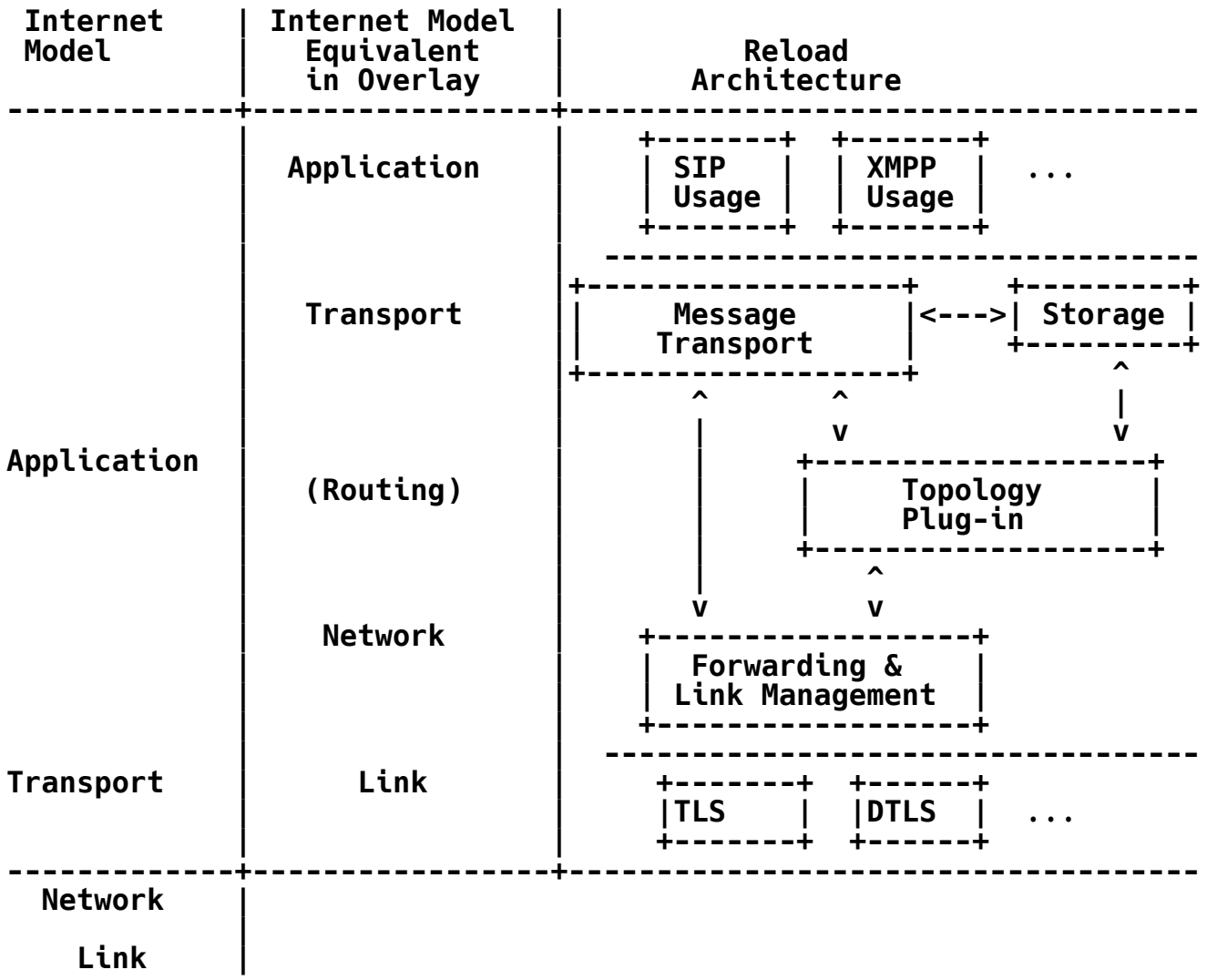
Storage: The Storage component is responsible for processing messages relating to the storage and retrieval of data. It talks directly to the Topology Plug-in to manage data replication and migration, and it talks to the Message Transport component to send and receive messages.

Topology Plug-in: The Topology Plug-in is responsible for implementing the specific overlay algorithm being used. It uses the Message Transport component to send and receive overlay management messages, the Storage component to manage data replication, and the Forwarding Layer to control hop-by-hop message forwarding. This component superficially parallels conventional routing algorithms, but is more tightly coupled to the Forwarding Layer, because there is no single "Routing Table" equivalent used by all overlay algorithms. The Topology Plug-in has two functions: constructing the local forwarding instructions and selecting the operational topology (i.e., creating links by sending overlay management messages).

Forwarding and Link Management Layer: Stores and implements the Routing Table by providing packet forwarding services between nodes. It also handles establishing new links between nodes, including setting up connections for overlay links across NATs using ICE.

Overlay Link Layer: Responsible for actually transporting traffic directly between nodes. Transport Layer Security (TLS) [RFC5246] and Datagram Transport Layer Security (DTLS) [RFC6347] are the currently defined "overlay link layer" protocols used by RELOAD for hop-by-hop communication. Each such protocol includes the appropriate provisions for per-hop framing and hop-by-hop ACKs needed by unreliable underlying transports. New protocols can be defined, as described in Sections 6.6.1 and 11.1. As this document defines only TLS and DTLS, we use those terms throughout the remainder of the document with the understanding that some future specification may add new overlay link layers.

To further clarify the roles of the various layers, the following figure parallels the architecture with each layer's role from an overlay perspective and implementation layer in the Internet:



In addition to the above components, nodes may communicate with a central provisioning infrastructure (not shown) to get configuration information, authentication credentials, and the initial set of nodes to communicate with to join the overlay.

1.2.1. Usage Layer

The top layer, called the Usage Layer, has application usages, such as the SIP Registration Usage [SIP-RELOAD], that use the abstract Message Transport Service provided by RELOAD. The goal of this layer is to implement application-specific usages of the generic overlay services provided by RELOAD. The Usage defines how a specific application maps its data into something that can be stored in the overlay, where to store the data, how to secure the data, and finally how applications can retrieve and use the data.

The architecture diagram shows both a SIP Usage and an XMPP Usage. A single application may require multiple usages; for example, a voicemail feature in a softphone application that stores links to the messages in the overlay would require a different usage than the type of rendezvous service of XMPP or SIP. A usage may define multiple Kinds of data that are stored in the overlay and may also rely on Kinds originally defined by other usages.

Because the security and storage policies for each Kind are dictated by the usage defining the Kind, the usages may be coupled with the Storage component to provide security policy enforcement and to implement appropriate storage strategies according to the needs of the usage. The exact implementation of such an interface is outside the scope of this specification.

1.2.2. Message Transport

The Message Transport component provides a generic message routing service for the overlay. The Message Transport layer is responsible for end-to-end message transactions. Each peer is identified by its location in the overlay, as determined by its Node-ID. A component that is a client of the Message Transport can perform two basic functions:

- Send a message to a given peer specified by Node-ID or to the peer responsible for a particular Resource-ID.

- Receive messages that other peers sent to a Node-ID or Resource-ID for which the receiving peer is responsible.

All usages rely on the Message Transport component to send and receive messages from peers. For instance, when a usage wants to store data, it does so by sending Store requests. Note that the Storage component and the Topology Plug-in are themselves clients of the Message Transport, because they need to send and receive messages from other peers.

The Message Transport Service is responsible for end-to-end reliability, which is accomplished by timer-based retransmissions. Unlike the Internet transport layer, however, this layer does not provide congestion control. RELOAD is a request-response protocol, with no more than two pairs of request-response messages used in typical transactions between pairs of nodes; therefore, there are no opportunities to observe and react to end-to-end congestion. As with all Internet applications, implementers are strongly discouraged from writing applications that react to loss by immediately retrying the transaction.

The Message Transport Service is similar to those described as providing "key-based routing" (KBR) [wikiKBR], although as RELOAD supports different overlay algorithms (including non-DHT overlay algorithms) that calculate keys (storage indices, not encryption keys) in different ways, the actual interface needs to accept Resource Names rather than actual keys.

The Forwarding and Link Management layers are responsible for maintaining the overlay in the face of changes in the available nodes and underlying network supporting the overlay (the Internet). They also handle congestion control between overlay neighbors, and exchange routing updates and data replicas in addition to forwarding end-to-end messages.

Real-world experience has shown that a fixed timeout for the end-to-end retransmission timer is sufficient for practical overlay networks. This timer is adjustable via the overlay configuration. As the overlay configuration can be rapidly updated, this value could be dynamically adjusted at coarse time scales, although algorithms for determining how to accomplish this are beyond the scope of this specification. In many cases, however, other means of improving network performance, such as having the Topology Plug-in remove lossy links from use in overlay routing or reducing the overall hop count of end-to-end paths, will be more effective than simply increasing the retransmission timer.

1.2.3. Storage

One of the major functions of RELOAD is storage of data, that is, allowing nodes to store data in the overlay and to retrieve data stored by other nodes or by themselves. The Storage component is responsible for processing data storage and retrieval messages. For instance, the Storage component might receive a Store request for a given resource from the Message Transport. It would then query the appropriate usage before storing the data value(s) in its local data store and sending a response to the Message Transport for delivery to the requesting node. Typically, these messages will come from other

nodes, but depending on the overlay topology, a node might be responsible for storing data for itself as well, especially if the overlay is small.

A peer's Node-ID determines the set of resources that it will be responsible for storing. However, the exact mapping between these is determined by the overlay algorithm in use. The Storage component will only receive a Store request from the Message Transport if this peer is responsible for that Resource-ID. The Storage component is notified by the Topology Plug-in when the Resource-IDs for which it is responsible change, and the Storage component is then responsible for migrating resources to other peers.

1.2.4. Topology Plug-in

RELOAD is explicitly designed to work with a variety of overlay algorithms. In order to facilitate this, the overlay algorithm implementation is provided by a Topology Plug-in so that each overlay can select an appropriate overlay algorithm that relies on the common RELOAD core protocols and code.

The Topology Plug-in is responsible for maintaining the overlay algorithm Routing Table, which is consulted by the Forwarding and Link Management Layer before routing a message. When connections are made or broken, the Forwarding and Link Management Layer notifies the Topology Plug-in, which adjusts the Routing Table as appropriate. The Topology Plug-in will also instruct the Forwarding and Link Management Layer to form new connections as dictated by the requirements of the overlay algorithm Topology. The Topology Plug-in issues periodic update requests through Message Transport to maintain and update its Routing Table.

As peers enter and leave, resources may be stored on different peers, so the Topology Plug-in also keeps track of which peers are responsible for which resources. As peers join and leave, the Topology Plug-in instructs the Storage component to issue resource migration requests as appropriate, in order to ensure that other peers have whatever resources they are now responsible for. The Topology Plug-in is also responsible for providing for redundant data storage to protect against loss of information in the event of a peer failure and to protect against compromised or subversive peers.

1.2.5. Forwarding and Link Management Layer

The Forwarding and Link Management Layer is responsible for getting a message to the next peer, as determined by the Topology Plug-in. This layer establishes and maintains the network connections as needed by the Topology Plug-in. This layer is also responsible for setting up connections to other peers through NATs and firewalls using ICE, and it can elect to forward traffic using relays for NAT and firewall traversal.

Congestion control is implemented at this layer to protect the Internet paths used to form the link in the overlay. Additionally, retransmission is performed to improve the reliability of end-to-end transactions. The relation of this layer to the Message Transport Layer can be likened to the relation of the link-level congestion control and retransmission in modern wireless networks ` to Internet transport protocols.

This layer provides a generic interface that allows the Topology Plug-in to control the overlay and resource operations and messages. Because each overlay algorithm is defined and functions differently, we generically refer to the table of other peers that the overlay algorithm maintains and uses to route requests as a Routing Table. The Topology Plug-in actually owns the Routing Table, and forwarding decisions are made by querying the Topology Plug-in for the next hop for a particular Node-ID or Resource-ID. If this node is the destination of the message, the message is delivered to the Message Transport.

This layer also utilizes a framing header to encapsulate messages as they are forwarded along each hop. This header aids reliability congestion control, flow control, etc. It has meaning only in the context of that individual link.

The Forwarding and Link Management Layer sits on top of the Overlay Link Layer protocols that carry the actual traffic. This specification defines how to use DTLS and TLS protocols to carry RELOAD messages.

1.3. Security

RELOAD's security model is based on each node having one or more public key certificates. In general, these certificates will be assigned by a central server, which also assigns Node-IDs, although self-signed certificates can be used in closed networks. These credentials can be leveraged to provide communications security for RELOAD messages. RELOAD provides communications security at three levels:

Connection level: Connections between nodes are secured with TLS, DTLS, or potentially some to-be-defined future protocol.

Message level: Each RELOAD message is signed.

Object Level: Stored objects are signed by the creating node.

These three levels of security work together to allow nodes to verify the origin and correctness of data they receive from other nodes, even in the face of malicious activity by other nodes in the overlay. RELOAD also provides access control built on top of these communications security features. Because the peer responsible for storing a piece of data can validate the signature on the data being stored, it can determine whether or not a given operation is permitted.

RELOAD also provides an optional shared-secret-based admission control feature using shared secrets and TLS pre-shared keys (PSK) or TLS Secure Remote Password (SRP). In order to form a TLS connection to any node in the overlay, a new node needs to know the shared overlay key, thus restricting access to authorized users only. This feature is used together with certificate-based access control, not as a replacement for it. It is typically used when self-signed certificates are being used but would generally not be used when the certificates were all signed by an enrollment server.

1.4. Structure of This Document

The remainder of this document is structured as follows.

- Section 3 provides definitions of terms used in this document.
- Section 4 provides an overview of the mechanisms used to establish and maintain the overlay.
- Section 5 provides an overview of the mechanism RELOAD provides to support other applications.
- Section 6 defines the protocol messages that RELOAD uses to establish and maintain the overlay.
- Section 7 defines the protocol messages that are used to store and retrieve data using RELOAD.
- Section 8 defines the Certificate Store Usages.
- Section 9 defines the TURN Server Usage needed to locate TURN (Traversal Using Relays around NAT) servers for NAT traversal.

- Section 10 defines a specific Topology Plug-in using a Chord-based algorithm.
- Section 11 defines the mechanisms that new RELOAD nodes use to join the overlay for the first time.
- Section 12 provides an extended example.

2. Requirements Language

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 RFC 2119 [RFC2119].

3. Terminology

Terms in this document are defined in-line when used and are also defined below for reference. The definitions in this section use terminology and concepts that are not explained until later in the specification.

Admitting Peer (AP): A peer in the overlay which helps the Joining Node join the Overlay.

Bootstrap Node: A network node used by Joining Nodes to help locate the Admitting Peer.

Client: A host that is able to store data in and retrieve data from the overlay, but does not participate in routing or data storage for the overlay.

Configuration Document: An XML document containing all the Overlay Parameters for one overlay instance.

Connection Table: Contains connection information for the set of nodes to which a node is directly connected, which include nodes that are not yet available for routing.

Destination List: A list of Node-IDs, Resource-IDs, and Opaque IDs through which a message is to be routed, in strict order. A single Node-ID, Resource-ID, or Opaque ID is a trivial form of Destination List. When multiple Node-IDs are specified, a Destination List is a loose source route. The list is reduced hop by hop, and does not include the source but does include the destination.

DHT: A distributed hash table. A DHT is an abstract storage service realized by storing the contents of the hash table across a set of peers.

ID: A generic term for any kind of identifiers in an Overlay. This document specifies an ID as being an Application-ID, a Kind-ID, a Node-ID, a transaction ID, a component ID, a response ID, a Resource-ID, or an Opaque ID.

Joining Node (JN): A node that is attempting to become a peer in a particular Overlay.

Kind: A Kind defines a particular type of data that can be stored in the overlay. Applications define new Kinds to store the data they use. Each Kind is identified with a unique integer called a Kind-ID.

Kind-ID: A unique 32-bit value identifying a Kind. Kind-IDs are either private or allocated by IANA (see Section 14.6).

Maximum Request Lifetime: The maximum time a request will wait for a response. This value is equal to the value of the overlay reliability value (defined in Section 11.1) multiplied by the number of transmissions (defined in Section 6.2.1), and so defaults to 15 seconds.

Node: The term "node" refers to a host that may be either a peer or a client. Because RELOAD uses the same protocol for both clients and peers, much of the text applies equally to both. Therefore, we use "node" when the text applies to both clients and peers, and we use the more specific term (i.e., "client" or "peer") when the text applies only to clients or only to peers.

Node-ID: A value of fixed but configurable length that uniquely identifies a node. Node-IDs of all 0s and all 1s are reserved. A value of 0 is not used in the wire protocol, but can be used to indicate an invalid node in implementations and APIs. The Node-ID of all 1s is used on the wire protocol as a wildcard.

Overlay Algorithm: An overlay algorithm defines the rules for determining which peers in an overlay store a particular piece of data and for determining a topology of interconnections amongst peers in order to find a piece of data.

Overlay Instance: A specific overlay algorithm and the collection of peers that are collaborating to provide read and write access to it. Any number of overlay instances can be running in an IP network at a time, and each operates in isolation of the others.

Overlay Parameters: A set of values that are shared among all nodes in an overlay. The overlay parameters are distributed in an XML document called the Configuration Document.

Peer: A host that is participating in the overlay. Peers are responsible for holding some portion of the data that has been stored in the overlay, and they are responsible for routing messages on behalf of other hosts as needed by the Overlay Algorithm.

Peer Admission: The act of admitting a node (the Joining Node) into an Overlay. After the admission process is over, the Joining Node is a fully functional peer of the overlay. During the admission process, the Joining Node may need to present credentials to prove that it has sufficient authority to join the overlay.

Resource: An object or group of objects stored in a P2P network.

Resource-ID: A value that identifies some resources and which is used as a key for storing and retrieving the resource. Often this is not human friendly/readable. One way to generate a Resource-ID is by applying a mapping function to some other unique name (e.g., user name or service name) for the resource. The Resource-ID is used by the distributed database algorithm to determine the peer or peers that are responsible for storing the data for the overlay. In structured P2P networks, Resource-IDs are generally fixed length and are formed by hashing the Resource Name. In unstructured networks, Resource Names may be used directly as Resource-IDs and may be of variable length.

Resource Name: The name by which a resource is identified. In unstructured P2P networks, the Resource Name is sometimes used directly as a Resource-ID. In structured P2P networks, the Resource Name is typically mapped into a Resource-ID by using the string as the input to hash function. Structured and unstructured P2P networks are described in [RFC5694]. A SIP resource, for example, is often identified by its AOR (address-of-record), which is an example of a Resource Name.

Responsible Peer: The peer that is responsible for a specific resource, as defined by the Topology Plug-in algorithm.

Routing Table: The set of directly connected peers which a node can use to forward overlay messages. In normal operation, these peers will all be in the Connection Table, but not vice versa, because some peers may not yet be available for routing. Peers may send

messages directly to peers that are in their Connection Tables, but may forward messages to peers that are not in their Connection Table only through peers that are in the Routing Table.

Successor Replacement Hold-Down Time: The amount of time to wait before starting replication when a new successor is found; it defaults to 30 seconds.

Transaction ID: A randomly chosen identifier selected by the originator of a request that is used to correlate requests and responses.

Usage: The definition of a set of data structures (data Kinds) that an application wants to store in the overlay. A usage may also define a set of network protocols (Application IDs) that can be tunneled over TLS or DTLS direct connections between nodes. For example, the SIP Usage defines a SIP registration data Kind, which contains information on how to reach a SIP endpoint, and two Application IDs corresponding to the SIP and SIPS protocols.

User: A physical person identified by the certificates assigned to them.

User Name: A name identifying a user of the overlay, typically used as a Resource Name or as a label on a resource that identifies the user owning the resource.

4. Overlay Management Overview

The most basic function of RELOAD is as a generic overlay network. Nodes need to be able to join the overlay, form connections to other nodes, and route messages through the overlay to nodes to which they are not directly connected. This section provides an overview of the mechanisms that perform these functions.

4.1. Security and Identification

The overlay parameters are specified in a Configuration Document. Because the parameters include security-critical information, such as the certificate signing trust anchors, the Configuration Document needs to be retrieved securely. The initial Configuration Document is either initially fetched over HTTPS or manually provisioned. Subsequent Configuration Document updates are received either as a result of being refreshed periodically by the configuration server, or, more commonly, by being flood-filled through the overlay, which allows for fast propagation once an update is pushed. In the latter case, updates are via digital signatures that trace back to the initial Configuration Document.

Every node in the RELOAD overlay is identified by a Node-ID. The Node-ID is used for three major purposes:

- To address the node itself.
- To determine the node's position in the overlay topology (if the overlay is structured; overlays do not need to be structured).
- To determine the set of resources for which the node is responsible.

Each node has a certificate [RFC5280] containing its Node-ID in a subjectAltName extension, which is unique within an overlay instance.

The certificate serves multiple purposes:

- It entitles the user to store data at specific locations in the Overlay Instance. Each data Kind defines the specific rules for determining which certificates can access each Resource-ID/Kind-ID pair. For instance, some Kinds might allow anyone to write at a given location, whereas others might restrict writes to the owner of a single certificate.
- It entitles the user to operate a node that has a Node-ID found in the certificate. When the node forms a connection to another peer, it uses this certificate so that a node connecting to it knows it is connected to the correct node. (Technically, a TLS or DTLS association with client authentication is formed.) In addition, the node can sign messages, thus providing integrity and authentication for messages which are sent from the node.
- It entitles the user to use the user name found in the certificate.

If a user has more than one device, typically they would get one certificate for each device. This allows each device to act as a separate peer.

RELOAD supports multiple certificate issuance models. The first is based on a central enrollment process, which allocates a unique name and Node-ID and puts them in a certificate for the user. All peers in a particular Overlay Instance have the enrollment server as a trust anchor and so can verify any other peer's certificate.

The second model is useful in settings, when a group of users want to set up an overlay network but are not concerned about attack by other users in the network. For instance, users on a LAN might want to set up a short-term ad hoc network without going to the trouble of

setting up an enrollment server. RELOAD supports the use of self-generated, self-signed certificates. When self-signed certificates are used, the node also generates its own Node-ID and user name. The Node-ID is computed as a digest of the public key, to prevent Node-ID theft. Note that the relevant cryptographic property for the digest is partial preimage resistance. Collision resistance is not needed, because an attacker who can create two nodes with the same Node-ID but a different public key obtains no advantage. This model is still subject to a number of known attacks (most notably, Sybil attacks [Sybil]) and can be safely used only in closed networks where users are mutually trusting. Another drawback of this approach is that the user's data is then tied to their key, so if a key is changed, any data stored under their Node-ID needs to be re-stored. This is not an issue for centrally issued Node-IDs provided that the Certification Authority (CA) reissues the same Node-ID when a new certificate is generated.

The general principle here is that the security mechanisms (TLS or DTLS at the data link layer and message signatures at the message transport layer) are always used, even if the certificates are self-signed. This allows for a single set of code paths in the systems, with the only difference being whether certificate verification is used to chain to a single root of trust.

4.1.1. Shared-Key Security

RELOAD also provides an admission control system based on shared keys. In this model, the peers all share a single key which is used to authenticate the peer-to-peer connections via TLS-PSK [RFC4279] or TLS-SRP [RFC5054].

4.2. Clients

RELOAD defines a single protocol that is used both as the peer protocol and as the client protocol for the overlay. Having a single protocol simplifies implementation, particularly for devices that may act in either role, and allows clients to inject messages directly into the overlay.

We use the term "peer" to identify a node in the overlay that routes messages for nodes other than those to which it is directly connected. Peers also have storage responsibilities. We use the term "client" to refer to nodes that do not have routing or storage responsibilities. When text applies to both peers and clients, we will simply refer to such devices as "nodes".

RELOAD's client support allows nodes that are not participating in the overlay as peers to utilize the same implementation and to benefit from the same security mechanisms as the peers. Clients possess and use certificates that authorize the user to store data at certain locations in the overlay. The Node-ID in the certificate is used to identify the particular client as a member of the overlay and to authenticate its messages.

In RELOAD, unlike some other designs, clients are not first-class entities. From the perspective of a peer, a client is a node that has connected to the overlay, but that has not yet taken steps to insert itself into the overlay topology. It might never do so (if it's a client), or it might eventually do so (if it's just a node that is taking a long time to join). The routing and storage rules for RELOAD provide for correct behavior by peers regardless of whether other nodes attached to them are clients or peers. Of course, a client implementation needs to know that it intends to be a client, but this localizes complexity only to that node.

For more discussion about the motivation for RELOAD's client support, see Appendix B.

4.2.1. Client Routing

Clients may insert themselves in the overlay in two ways:

- Establish a connection to the peer responsible for the client's Node-ID in the overlay. Then, requests may be sent from/to the client using its Node-ID in the same manner as if it were a peer, because the responsible peer in the overlay will handle the final step of routing to the client. This may require a TURN [RFC5766] relay in cases where NATs or firewalls prevent a client from forming a direct connection with its responsible peer. Note that clients that choose this option need to process Update messages from the peer (Section 6.4.2.3). These updates can indicate that the peer is no longer responsible for the client's Node-ID. The client would then need to form a connection to the appropriate peer. Failure to do so will result in the client no longer receiving messages.

- Establish a connection with an arbitrary peer in the overlay (perhaps based on network proximity or an inability to establish a direct connection with the responsible peer). In this case, the client will rely on RELOAD's Destination List feature (Section 6.3.2.2) to ensure reachability. The client can initiate requests, and any node in the overlay that knows the Destination List to its current location can reach it, but the client is not directly reachable using only its Node-ID. If the client is to

receive incoming requests from other members of the overlay, the Destination List needed to reach the client needs to be learnable via other mechanisms, such as being stored in the overlay by a usage. A client connected this way using a certificate with only a single Node-ID can proceed to use the connection without performing an Attach (Section 6.5.1). A client wishing to connect using this mechanism with a certificate with multiple Node-IDs can use a Ping (Section 6.5.3) to probe the Node-ID of the node to which it is connected before performing the Attach.

4.2.2. Minimum Functionality Requirements for Clients

A node may act as a client simply because it does not have the capacity or need to act as a peer in the overlay, or because it does not even have an implementation of the Topology Plug-in defined in Section 6.4.1, needed to act as a peer in the overlay. In order to exchange RELOAD messages with a peer, a client needs to meet a minimum level of functionality. Such a client will:

- Implement RELOAD's connection-management operations that are used to establish the connection with the peer.
- Implement RELOAD's data retrieval methods (with client functionality).
- Be able to calculate Resource-IDs used by the overlay.
- Possess security credentials needed by the overlay that it is implementing.

A client speaks the same protocol as the peers, knows how to calculate Resource-IDs, and signs its requests in the same manner as peers. While a client does not necessarily require a full implementation of the overlay algorithm, calculating the Resource-ID requires an implementation of an appropriate algorithm for the overlay.

4.3. Routing

This section discusses the capabilities of RELOAD's routing layer and the protocol features used to implement the capabilities, and provides a brief overview of how they are used. Appendix A discusses some alternative designs and the trade-offs that would be necessary to support them.

RELOAD's routing provides the following capabilities:

Resource-based Routing: RELOAD supports routing messages based solely on the name of the resource. Such messages are delivered to a node that is responsible for that resource. Both structured and unstructured overlays are supported, so the route may not be deterministic for all Topology Plug-ins.

Node-based Routing: RELOAD supports routing messages to a specific node in the overlay.

Clients: RELOAD supports requests from and to clients that do not participate in overlay routing. The clients are located via either of the mechanisms described above.

NAT Traversal: RELOAD supports establishing and using connections between nodes separated by one or more NATs, including locating peers behind NATs for those overlays allowing/requiring it.

Low State: RELOAD's routing algorithms do not require significant state (i.e., state linear or greater in the number of outstanding messages that have passed through it) to be stored on intermediate peers.

Routability in Unstable Topologies: Overlay topology changes constantly in an overlay of moderate size due to the failure of individual nodes and links in the system. RELOAD's routing allows peers to reroute messages when a failure is detected, and replies can be returned to the requesting node as long as the peers that originally forwarded the successful request do not fail before the response is returned.

RELOAD's routing utilizes three basic mechanisms:

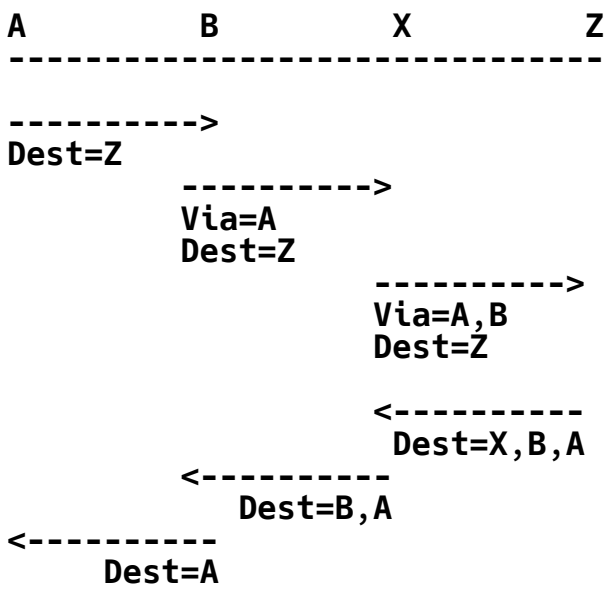
Destination Lists: While, in principle, it is possible to just inject a message into the overlay with a single Node-ID as the destination, RELOAD provides a source-routing capability in the form of "Destination Lists". A Destination List provides a list of the nodes through which a message flows in order (i.e., it is loose source routed). The minimal Destination List contains just a single value.

Via Lists: In order to allow responses to follow the same path as requests, each message also contains a "Via List", which is appended to by each node a message traverses. This Via List can then be inverted and used as a Destination List for the response.

RouteQuery: The RouteQuery method allows a node to query a peer for the next hop it will use to route a message. This method is useful for diagnostics and for iterative routing (see Section 6.4.2.4).

The basic routing mechanism that RELOAD uses is symmetric recursive. We will first describe symmetric recursive routing and then discuss its advantages in terms of the requirements discussed above.

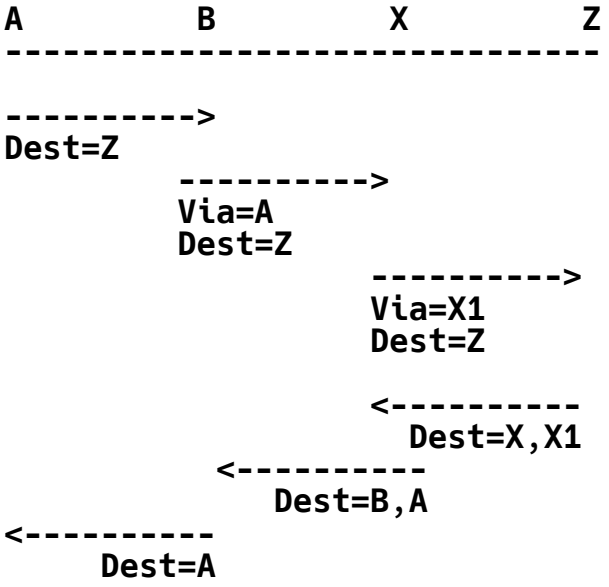
Symmetric recursive routing requires that a request message follow a path through the overlay to the destination: each peer forwards the message closer to its destination. The return path of the response goes through the same nodes as the request (though it may also go through some new intermediate nodes due to topology changes). Note that a failure on the reverse path caused by a topology change after the request was sent will be handled by the end-to-end retransmission of the response as described in Section 6.2.1. For example, the following figure shows a message following a route from A to Z through B and X:



Note that this figure does not indicate whether A is a client or peer. A forwards its request to B, and the response is returned to A in the same manner regardless of A's role in the overlay.

This figure shows use of full Via Lists by intermediate peers B and X. However, if B and/or X are willing to store state, then they may elect to truncate the lists and save the truncated information internally using the transaction ID as a key to allow it to be retrieved later. Later, when the response message arrives, the

transaction ID would be used to recover the truncated information and return the response message along the path from which the request arrived. This option requires a greater amount of state to be stored on intermediate peers, but saves a small amount of bandwidth and reduces the need for modifying the message en route. Selection of this mode of operation is a choice for the individual peer; the techniques are interoperable even on a single message. The figure below shows B using full Via Lists, but X truncating them to X1 and saving the state internally.



As before, when B receives the message, B creates a Via List consisting of [A]. However, instead of sending [A, B], X creates an opaque ID X1 which maps internally to [A, B] (perhaps by being an encryption of [A, B]) and then forwards to Z with only X1 as the Via List. When the response arrives at X, it maps X1 back to [A, B], then inverts it to produce the new Destination List [B, A], and finally routes it to B.

RELOAD also supports a basic iterative "routing" mode, in which the intermediate peers merely return a response indicating the next hop, but do not actually forward the message to that next hop themselves. Iterative routing is implemented using the RouteQuery method (see Section 6.4.2.4), which requests this behavior. Note that iterative routing is selected only by the initiating node.

4.4. Connectivity Management

In order to provide efficient routing, a peer needs to maintain a set of direct connections to other peers in the Overlay Instance. Due to the presence of NATs, these connections often cannot be formed directly. Instead, we use the Attach request to establish a connection. Attach uses Interactive Connectivity Establishment (ICE) [RFC5245] to establish the connection. It is assumed that the reader is familiar with ICE.

Say that peer A wishes to form a direct connection to peer B, either to join the overlay or to add more connections in its Routing Table. It gathers ICE candidates and packages them up in an Attach request, which it sends to B through usual overlay routing procedures. B does its own candidate gathering and sends back a response with its candidates. A and B then do ICE connectivity checks on the candidate pairs. The result is a connection between A and B. At this point, A and B MAY send messages directly between themselves without going through other overlay peers. In other words, A and B are in each other's Connection Tables. They MAY then execute an Update process, resulting in additions to each other's Routing Tables, and may then become able to route messages through each other to other overlay nodes.

There are two cases where Attach is not used. The first is when a peer is joining the overlay and is not connected to any peers. In order to support this case, a small number of bootstrap nodes typically need to be publicly accessible so that new peers can directly connect to them. Section 11 contains more detail on this. The second case is when a client connects to a peer at an arbitrary IP address, rather than to its responsible peer, as described in the second bullet point of Section 4.2.1.

In general, a peer needs to maintain connections to all of the peers near it in the Overlay Instance and to enough other peers to have efficient routing (the details on what "enough" and "near" mean depend on the specific overlay). If a peer cannot form a connection to some other peer, this is not necessarily a disaster; overlays can route correctly even without fully connected links. However, a peer needs to try to maintain the specified Routing Table defined by the Topology Plug-in algorithm and needs to form new connections if it detects that it has fewer direct connections than specified by the algorithm. This also implies that peers, in accordance with the Topology Plug-in algorithm, need to periodically verify that the connected peers are still alive and, if not, need to try to re-form the connections or form alternate ones. See Section 10.7.4.3 for an example on how a specific overlay algorithm implements these constraints.

4.5. Overlay Algorithm Support

The Topology Plug-in allows RELOAD to support a variety of overlay algorithms. This specification defines a DHT based on Chord, which is mandatory to implement, but the base RELOAD protocol is designed to support a variety of overlay algorithms. The information needed to implement this DHT is fully contained in this specification, but it is easier to understand if you are familiar with Chord-based [Chord] DHTs. A nice tutorial can be found at [wikiChord].

4.5.1. Support for Pluggable Overlay Algorithms

RELOAD defines three methods for overlay maintenance: Join, Update, and Leave. However, the contents of these messages, when they are sent, and their precise semantics are specified by the actual overlay algorithm, which is specified by configuration for all nodes in the overlay and thus is known to nodes before they attempt to join the overlay. RELOAD merely provides a framework of commonly needed methods that provide uniformity of notation (and ease of debugging) for a variety of overlay algorithms.

4.5.2. Joining, Leaving, and Maintenance Overview

When a new peer wishes to join the Overlay Instance, it will need a Node-ID that it is allowed to use and a set of credentials which match that Node-ID. When an enrollment server is used, the Node-ID used is the one found in the certificate received from the enrollment server. The details of the joining procedure are defined by the overlay algorithm, but the general steps for joining an Overlay Instance are:

- Form connections to some other peers.
- Acquire the data values this peer is responsible for storing.
- Inform the other peers which were previously responsible for that data that this peer has taken over responsibility.

The first thing the peer needs to do is to form a connection to some bootstrap node. Because this is the first connection the peer makes, these nodes will need public IP addresses so that they can be connected to directly. Once a peer has connected to one or more bootstrap nodes, it can form connections in the usual way, by routing Attach messages through the overlay to other nodes. After a peer has connected to the overlay for the first time, it can cache the set of past adjacencies which have public IP addresses and can attempt to use them as future bootstrap nodes. Note that this requires some

notion of which addresses are likely to be public as discussed in Section 9.

After a peer has connected to a bootstrap node, it then needs to take up its appropriate place in the overlay. This requires two major operations:

- Form connections to other peers in the overlay to populate its Routing Table.
- Get a copy of the data it is now responsible for storing, and assume responsibility for that data.

The second operation is performed by contacting the Admitting Peer (AP), the node which is currently responsible for the relevant section of the overlay.

The details of this operation depend mostly on the overlay algorithm involved, but a typical case would be:

1. JN sends a Join request to AP announcing its intention to join.
2. AP sends a Join response.
3. AP does a sequence of Stores to JN to give it the data it will need.
4. AP does Updates to JN and to other peers to tell them about its own Routing Table. At this point, both JN and AP consider JN responsible for some section of the Overlay Instance.
5. JN makes its own connections to the appropriate peers in the Overlay Instance.

After this process completes, JN is a full member of the Overlay Instance and can process Store/Fetch requests.

Note that the first node is a special case. When ordinary nodes cannot form connections to the bootstrap nodes, then they are not part of the overlay. However, the first node in the overlay can obviously not connect to other nodes. In order to support this case, potential first nodes (which can also initially serve as bootstrap nodes) need to somehow be instructed that they are the entire overlay, rather than part of an existing overlay (e.g., by comparing their IP address to the bootstrap IP addresses in the configuration file).

Note that clients do not perform either of these operations.

4.6. First-Time Setup

Previous sections addressed how RELOAD works after a node has connected. This section provides an overview of how users get connected to the overlay for the first time. RELOAD is designed so that users can start with the name of the overlay they wish to join and perhaps an account name and password, and can leverage these into having a working peer with minimal user intervention. This helps avoid the problems that have been experienced with conventional SIP clients in which users need to manually configure a large number of settings.

4.6.1. Initial Configuration

In the first phase of the setup process, the user starts with the name of the overlay and uses it to download an initial set of overlay configuration parameters. The node does a DNS SRV [RFC2782] lookup on the overlay name to get the address of a configuration server. It can then connect to this server with HTTPS [RFC2818] to download a Configuration Document which contains the basic overlay configuration parameters as well as a set of bootstrap nodes which can be used to join the overlay. The details of the relationships between names in the HTTPS certificates and the overlay names are described in Section 11.2.

If a node already has the valid Configuration Document that it received by an out-of-band method, this step can be skipped. Note that this out-of-band method needs to provide authentication and integrity, because the Configuration Document contains the trust anchors used by the overlay.

4.6.2. Enrollment

If the overlay is using centralized enrollment, then a user needs to acquire a certificate before joining the overlay. The certificate attests both to the user's name within the overlay and to the Node-IDs which they are permitted to operate. In this case, the Configuration Document will contain the address of an enrollment server which can be used to obtain such a certificate and will also contain the trust anchor, so this document must be retrieved securely (see Section 11.2). The enrollment server may (and probably will) require some sort of account name for the user and a password before issuing the certificate. The enrollment server's ability to ensure attackers cannot get a large number of certificates for the overlay is one of the cornerstones of RELOAD's security.

4.6.3. Diagnostics

Significant advice around managing a RELOAD overlay and extensions for diagnostics are described in [P2P-DIAGNOSTICS].

5. Application Support Overview

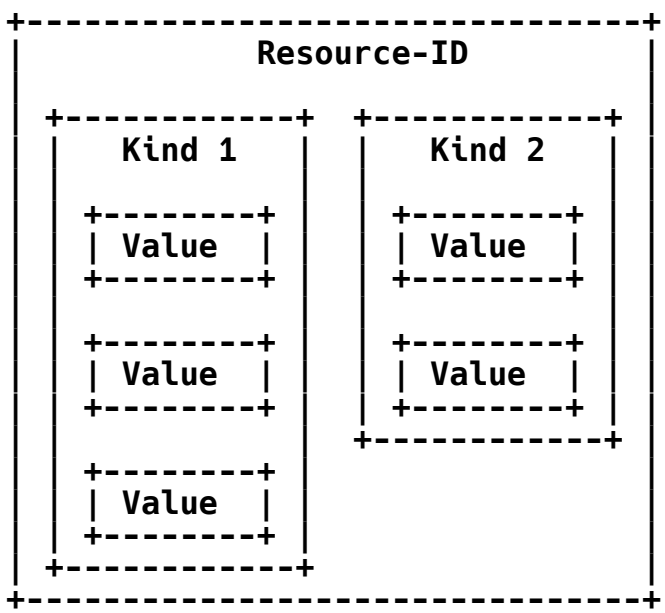
RELOAD is not intended to be used alone, but rather as a substrate for other applications. These applications can use RELOAD for a variety of purposes:

- To store data in the overlay and to retrieve data stored by other nodes.
- As a discovery mechanism for services such as TURN.
- To form direct connections which can be used to transmit application-level messages without using the overlay.

This section provides an overview of these services.

5.1. Data Storage

RELOAD provides operations to Store and Fetch data. Each location in the Overlay Instance is referenced by a Resource-ID. However, each location may contain data elements corresponding to multiple Kinds (e.g., certificate and SIP registration). Similarly, there may be multiple elements of a given Kind, as shown below:



Each Kind is identified by a Kind-ID, which is a code point either assigned by IANA or allocated out of a private range. As part of the Kind definition, protocol designers may define constraints (such as limits on size) on the values which may be stored. For many Kinds, the set may be restricted to a single value, while some sets may be allowed to contain multiple identical items, and others may have only unique items. Note that a Kind may be employed by multiple usages, and new usages are encouraged to use previously defined Kinds where possible. We define the following data models in this document, although other usages can define their own structures:

single value: There can be at most one item in the set, and any value overwrites the previous item.

array: Many values can be stored and addressed by a numeric index.

dictionary: The values stored are indexed by a key. Often, this key is one of the values from the certificate of the peer sending the Store request.

In order to protect stored data from tampering by other nodes, each stored value is individually digitally signed by the node which created it. When a value is retrieved, the digital signature can be verified to detect tampering. If the certificate used to verify the stored value signature expires, the value can no longer be retrieved (although it may not be immediately garbage collected by the storing node), and the creating node will need to store the value again if it desires that the stored value continue to be available.

5.1.1. Storage Permissions

A major issue in peer-to-peer storage networks is minimizing the burden of becoming a peer and, in particular, minimizing the amount of data which any peer needs to store for other nodes. RELOAD addresses this issue by allowing any given node to store data only at a small number of locations in the overlay, with those locations being determined by the node's certificate. When a peer uses a Store request to place data at a location authorized by its certificate, it signs that data with the private key that corresponds to its certificate. Then the peer responsible for storing the data is able to verify that the peer issuing the request is authorized to make that request. Each data Kind defines the exact rules for determining what certificate is appropriate.

The most natural rule is that a certificate authorizes a user to store data keyed with their user name X. Thus, only a user with a certificate for "alice@example.org" could write to that location in

the overlay (see Section 11.3). However, other usages can define any rules they choose, including publicly writable values.

The digital signature over the data serves two purposes. First, it allows the peer responsible for storing the data to verify that this Store is authorized. Second, it provides integrity for the data. The signature is saved along with the data value (or values) so that any reader can verify the integrity of the data. Of course, the responsible peer can "lose" the value, but it cannot undetectably modify it.

The size requirements of the data being stored in the overlay are variable. For instance, a SIP AOR and voicemail differ widely in the storage size. RELOAD leaves it to the usage and overlay configuration to limit size imbalances of various Kinds.

5.1.2. Replication

Replication in P2P overlays can be used to provide:

persistence: if the responsible peer crashes and/or if the storing peer leaves the overlay

security: to guard against DoS attacks by the responsible peer or routing attacks to that responsible peer

load balancing: to balance the load of queries for popular resources

A variety of schemes are used in P2P overlays to achieve some of these goals. Common techniques include replicating on neighbors of the responsible peer, randomly locating replicas around the overlay, and replicating along the path to the responsible peer.

The core RELOAD specification does not specify a particular replication strategy. Instead, the first level of replication strategies is determined by the overlay algorithm, which can base the replication strategy on its particular topology. For example, Chord places replicas on successor peers, which will take over responsibility if the responsible peer fails [Chord].

If additional replication is needed, for example, if data persistence is particularly important for a particular usage, then that usage may specify additional replication, such as implementing random replications by inserting a different well-known constant into the Resource Name used to store each replicated copy of the resource. Such replication strategies can be added independently of the underlying algorithm, and their usage can be determined based on the needs of the particular usage.

5.2. Usages

By itself, the distributed storage layer provides only the infrastructure on which applications are built. In order to do anything useful, a usage needs to be defined. Each usage needs to specify several things:

- Register Kind-ID code points for any Kinds that the usage defines (Section 14.6).
- Define the data structure for each of the Kinds (the value member in Section 7.2). If the data structure contains character strings, conversion rules between characters and the binary storage need to be specified.
- Define access control rules for each of the Kinds (Section 7.3).
- Define how the Resource Name is used to form the Resource-ID where each Kind is stored.
- Describe how values will be merged when a network partition is being healed.

The Kinds defined by a usage may also be applied to other usages. However, a need for different parameters, such as a different access control model, would imply the need to create a new Kind.

5.3. Service Discovery

RELOAD does not currently define a generic service discovery algorithm as part of the base protocol, although a simplistic TURN-specific discovery mechanism is provided. A variety of service discovery algorithms can be implemented as extensions to the base protocol, such as the service discovery algorithm ReDIR [opendht-sigcomm05] and [REDIR-RELOAD].

5.4. Application Connectivity

There is no requirement that a RELOAD Usage needs to use RELOAD's primitives for establishing its own communication if it already possesses its own means of establishing connections. For example, one could design a RELOAD-based resource discovery protocol which used HTTP to retrieve the actual data.

For more common situations, however, it is the overlay itself -- rather than an external authority such as DNS -- which is used to establish a connection. RELOAD provides connectivity to applications using the AppAttach method. For example, if a P2PSIP node wishes to

establish a SIP dialog with another P2PSIP node, it will use AppAttach to establish a direct connection with the other node. This new connection is separate from the peer protocol connection. It is a dedicated DTLS or TLS flow used only for the SIP dialog.

6. Overlay Management Protocol

This section defines the basic protocols used to create, maintain, and use the RELOAD overlay network. We start by defining the basic concept of how message destinations are interpreted when routing messages. We then describe the symmetric recursive routing model, which is RELOAD's default routing algorithm. Finally, we define the message structure and the messages used to join and maintain the overlay.

6.1. Message Receipt and Forwarding

When a node receives a message, it first examines the overlay, version, and other header fields to determine whether the message is one it can process. If any of these are incorrect, as defined in Section 6.3.2, it is an error and the message MUST be discarded. The peer SHOULD generate an appropriate error, but local policy can override this and cause the message to be silently dropped.

Once the peer has determined that the message is correctly formatted (note that this does not include signature-checking on intermediate nodes as the message may be fragmented), it examines the first entry on the Destination List. There are three possible cases here:

- The first entry on the Destination List is an ID for which the peer is responsible. A peer is always responsible for the wildcard Node-ID. Handling of this case is described in Section 6.1.1.

- The first entry on the Destination List is an ID for which another peer is responsible. Handling of this case is described in Section 6.1.2.

- The first entry on the Destination List is an opaque ID that is being used for Destination List compression. Handling of this case is described in Section 6.1.3. Note that opaque IDs can be distinguished from Node-IDs and Resource-IDs on the wire as described in Section 6.3.2.2.

These cases are handled as discussed below.

6.1.1. Responsible ID

If the first entry on the Destination List is an ID for which the peer is responsible, there are several (mutually exclusive) subcases to consider.

- If the entry is a Resource-ID, then it MUST be the only entry on the Destination List. If there are other entries, the message MUST be silently dropped. Otherwise, the message is destined for this node, so the node MUST verify the signature as described in Section 7.1 and MUST pass it to the upper layers. "Upper layers" is used here to mean the components above the "Overlay Link Service Boundary" line in the figure in Section 1.2.

- If the entry is a Node-ID which equals this node's Node-ID, then the message is destined for this node. If it is the only entry on the Destination List, the message is destined for this node and so the node passes it to the upper layers. Otherwise, the node removes the entry from the Destination List and repeats the routing process with the next entry on the Destination List. If the message is a response and list compression was used, then the node first modifies the Destination List to reinsert the saved state, e.g., by unpacking any opaque IDs.

- If the entry is the wildcard Node-ID (all "1"s), the message is destined for this node, and the node passes the message to the upper layers. A message with a wildcard Node-ID as its first entry is never forwarded; it is consumed locally.

- If the entry is a Node-ID which is not equal to this node, then the node MUST drop the message silently unless the Node-ID corresponds to a node which is directly connected to this node (i.e., a client). In the latter case, the node MUST attempt to forward the message to the destination node as described in the next section (though this may fail for connectivity reasons, because the TTL has expired, or because of some other error.)

Note that this process implies that in order to address a message to "the peer that controls region X", a sender sends to Resource-ID X, not Node-ID X.

6.1.2. Other ID

If the first entry on the Destination List is neither an opaque ID nor an ID the peer is responsible for, then the peer MUST forward the message towards that entry. This means that it MUST select one of the peers to which it is connected and which is most likely to be responsible (according to the Topology Plug-in) for the first entry

on the Destination List. For the CHORD-RELOAD topology, the routing to the most likely responsible node is explained in Section 10.3. If the first entry on the Destination List is in the peer's Connection Table, the peer MUST forward the message to that peer directly. Otherwise, the peer consults the Routing Table to forward the message.

Any intermediate peer which forwards a RELOAD request MUST ensure that if it receives a response to that message, the response can be routed back through the set of nodes through which the request passed. The peer selects one of these approaches:

- The peer can add an entry to the Via List in the forwarding header that will enable it to determine the correct node. This is done by appending to the Via List the Node-ID of the node from which the request was received.

- The peer can keep per-transaction state which will allow it to determine the correct node.

As an example of the first strategy, consider an example with nodes A, B, C, D, and E. If node D receives a message from node C with Via List [A, B], then D would forward to the next node E with Via List [A, B, C]. Now, if E wants to respond to the message, it reverses the Via List to produce the Destination List, resulting in [D, C, B, A]. When D forwards the response to C, the Destination List will contain [C, B, A].

As an example of the second strategy, if node D receives a message from node C with transaction ID X (as assigned by A) and Via List [A, B], it could store [X, C] in its state database and forward the message with the Via List unchanged. When D receives the response, it consults its state database for transaction ID X, determines that the request came from C, and forwards the response to C.

Intermediate peers which modify the Via List are not required to simply add entries. The only requirement is that the peer MUST be able to reconstruct the correct Destination List on the return route. RELOAD provides explicit support for this functionality in the form of opaque IDs, which can replace any number of Via List entries.

For instance, in the above example, Node D might send E a Via List containing only the opaque ID I. E would then use the Destination List [D, I] to send its return message. When D processes this Destination List, it would detect that I is an opaque ID, recover the Via List [A, B, C], and reverse that to produce the correct Destination List [C, B, A] before sending it to C. This feature is called "list compression". Possibilities for an opaque ID include a

compressed and/or encrypted version of the original Via List and an index into a state database containing the original Via List, but the details are a local matter.

No matter what mechanism for storing Via List state is used, if an intermediate peer exits the overlay, then on the return trip the message cannot be forwarded and will be dropped. The ordinary timeout and retransmission mechanisms provide stability over this type of failure.

Note that if an intermediate peer retains per-transaction state instead of modifying the Via List, it needs some mechanism for timing out that state; otherwise, its state database will grow without bound. Whatever algorithm is used, unless a FORWARD_CRITICAL forwarding option (Section 6.3.2.3) or an overlay configuration option explicitly indicates this state is not needed, the state MUST be maintained for at least the value of the overlay-reliability-timer configuration parameter and MAY be kept longer. Future extensions, such as [P2PSIP-RELAY], may define mechanisms for determining when this state does not need to be retained.

There is no requirement to ensure that a request issued after the receipt of a response follows the same path as the response. As a consequence, there is no requirement to use either of the mechanisms described above (Via List or state retention) when processing a response message.

A node receiving a request from another node MUST ensure that any response to that request exits that node with a Destination List equal to the concatenation of the Node-ID of the node from which the request was received with the Via List in the original request. The intermediate node normally learns the Node-ID that the other node is using via an Attach, but a node using a certificate with a single Node-ID MAY elect not to send an Attach (see Section 4.2.1, bullet 2). If a node with a certificate with multiple Node-IDs attempts to route a message other than a Ping or Attach through a node without performing an Attach, the receiving node MUST reject the request with an Error_Forbidden error. The node MUST implement support for returning responses to a Ping or Attach request made by a Joining Node Attaching to its responsible peer.

6.1.3. Opaque ID

If the first entry on the Destination List is an opaque ID (e.g., a compressed Via List), the peer MUST replace the entry with the original Via List that it replaced and then re-examine the Destination List to determine which of the three cases in Section 6.1 now applies.

6.2. Symmetric Recursive Routing

This section defines RELOAD's Symmetric Recursive Routing algorithm, which is the default algorithm used by nodes to route messages through the overlay. All implementations MUST implement this routing algorithm. An overlay MAY be configured to use alternative routing algorithms, and alternative routing algorithms MAY be selected on a per-message basis. That is, a node in an overlay which supports Symmetric Recursive Routing and some other routing algorithm called XXX might use Symmetric Recursive Routing some of the time and XXX at other times.

6.2.1. Request Origination

In order to originate a message to a given Node-ID or Resource-ID, a node MUST construct an appropriate Destination List. The simplest such Destination List is a single entry containing the Node-ID or Resource-ID. The resulting message MUST be forwarded to its destination via the normal overlay routing mechanisms. The node MAY also construct a more complicated Destination List for source routing.

Once the message is constructed, the node sends the message to an adjacent peer. If the first entry on the Destination List is directly connected, then the message MUST be routed down that connection. Otherwise, the Topology Plug-in MUST be consulted to determine the appropriate next hop.

Parallel requests for a resource are a common solution to improve reliability in the face of churn or subversive peers. Parallel searches for usage-specified replicas are managed by the usage layer, for instance, by having the usage store data at multiple Resource-IDs, with the requesting node sending requests to each of those Resource-IDs. However, a single request MAY also be routed through multiple adjacent peers, even when they are known to be suboptimal, to improve reliability [vulnerabilities-acsac04]. Such parallel searches MAY be specified by the Topology Plug-in, in which case it would return multiple next hops and the request would be routed to all of them.

Because messages can be lost in transit through the overlay, RELOAD incorporates an end-to-end reliability mechanism. When an originating node transmits a request, it MUST set a timer to the current overlay-reliability-timer. If a response has not been received when the timer fires, the request MUST be retransmitted with the same transaction identifier. The request MAY be retransmitted up to 4 times, for a total of 5 messages. After the timer for the fifth transmission fires, the message MUST be considered to have failed.

Although the originating node will be doing both end-to-end and hop-by-hop retransmissions, the end-by-end retransmission procedure is not followed by intermediate nodes. They follow the hop-by-hop reliability procedure described in Section 6.6.3.

The above algorithm can result in multiple requests being delivered to a node. Receiving nodes MUST generate semantically equivalent responses to retransmissions of the same request (this can be determined by the transaction ID) if the request is received within the maximum request lifetime (15 seconds). For some requests (e.g., Fetch), this can be accomplished merely by processing the request again. For other requests (e.g., Store), it may be necessary to maintain state for the duration of the request lifetime.

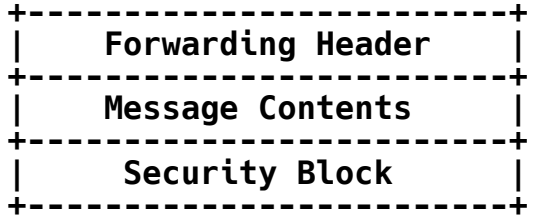
6.2.2. Response Origination

When a peer sends a response to a request using this routing algorithm, it MUST construct the Destination List by reversing the order of the entries on the Via List. This has the result that the response traverses the same peers as the request traversed, except in reverse order (symmetric routing) and possibly with extra nodes (loose routing).

6.3. Message Structure

RELOAD is a message-oriented request/response protocol. The messages are encoded using binary fields. All integers are represented in network byte order. The general philosophy behind the design was to use Type, Length, Value (TLV) fields to allow for extensibility. However, for the parts of a structure that were required in all messages, we just define these in a fixed position, as adding a type and length for them is unnecessary and would only increase bandwidth and introduce new potential interoperability issues.

Each message has three parts, which are concatenated, as shown below:



The contents of these parts are as follows:

Forwarding Header: Each message has a generic header which is used to forward the message between peers and to its final destination. This header is the only information that an intermediate peer (i.e., one that is not the target of a message) needs to examine. Section 6.3.2 describes the format of this part.

Message Contents: The message being delivered between the peers. From the perspective of the forwarding layer, the contents are opaque; however, they are interpreted by the higher layers. Section 6.3.3 describes the format of this part.

Security Block: A security block containing certificates and a digital signature over the "Message Contents" section. Note that this signature can be computed without parsing the message contents. All messages MUST be signed by their originator. Section 6.3.4 describes the format of this part.

6.3.1. Presentation Language

The structures defined in this document are defined using a C-like syntax based on the presentation language used to define TLS [RFC5246]. Advantages of this style include:

- It is familiar enough that most readers can grasp it quickly.
- The ability to define nested structures allows a separation between high-level and low-level message structures.
- It has a straightforward wire encoding that allows quick implementation, but the structures can be comprehended without knowing the encoding.
- It is possible to mechanically compile encoders and decoders.

Several idiosyncrasies of this language are worth noting:

- All lengths are denoted in bytes, not objects.
- Variable-length values are denoted like arrays, with angle brackets.
- "select" is used to indicate variant structures.

For instance, "uint16 array<0..2^8-2>;" represents up to 254 bytes, which corresponds to up to 127 values of two bytes (16 bits) each.

A repetitive structure member shares a common notation with a member containing a variable-length block of data. The latter always starts with "opaque", whereas the former does not. For instance, the following denotes a variable block of data:

```
opaque data<0..2^32-1>;
```

whereas the following denotes a list of 0, 1, or more instances of the Name element:

```
Name names<0..2^32-1>;
```

6.3.1.1. Common Definitions

This section provides an introduction to the presentation language used throughout RELOAD.

An enum represents an enumerated type. The values associated with each possibility are represented in parentheses, and the maximum value is represented as a nameless value, for purposes of describing the width of the containing integral type. For instance, Boolean represents a true or false:

```
enum { false(0), true(1), (255) } Boolean;
```

A boolean value is either a 1 or a 0. The max value of 255 indicates that this is represented as a single byte on the wire.

The NodeId, shown below, represents a single Node-ID.

```
typedef opaque       NodeId[NodeIdLength];
```

A NodeId is a fixed-length structure represented as a series of bytes, with the most significant byte first. The length is set on a per-overlay basis within the range of 16-20 bytes (128 to 160 bits). (See Section 11.1 for how NodeIdLength is set.) Note that the use of "typedef" here is an extension to the TLS language, but its meaning should be relatively obvious. Also note that the [size] syntax defines a fixed-length element that does not include the length of the element in the on-the-wire encoding.

A ResourceId, shown below, represents a single Resource-ID.

```
typedef opaque       ResourceId<0..2^8-1>;
```

Like a NodeId, a ResourceId is an opaque string of bytes, but unlike NodeIds, ResourceIds are variable length, up to 254 bytes (2040 bits) in length. On the wire, each ResourceId is preceded by a single

length byte (allowing lengths up to 255 bytes). Thus, the 3-byte value "FOO" would be encoded as: 03 46 4f 4f. Note the < range > syntax defines a variable length element that includes the length of the element in the on-the-wire encoding. The number of bytes to encode the length on the wire is derived by range; i.e., it is the minimum number of bytes which can encode the largest range value.

A more complicated example is IpAddressPort, which represents a network address and can be used to carry either an IPv6 or IPv4 address:

```
enum { invalidAddressType(0), ipv4_address(1), ipv6_address(2),
     (255) } AddressType;

struct {
  uint32                  addr;
  uint16                  port;
} IPv4AddrPort;

struct {
  uint128                 addr;
  uint16                  port;
} IPv6AddrPort;

struct {
  AddressType             type;
  uint8                   length;

  select (type) {
    case ipv4_address:
       IPv4AddrPort       v4addr_port;

    case ipv6_address:
       IPv6AddrPort       v6addr_port;

    /* This structure can be extended */
  };
} IpAddressPort;
```

The first two fields in the structure are the same no matter what kind of address is being represented:

type: The type of address (IPv4 or IPv6).

length: The length of the rest of the structure.

By having the type and the length appear at the beginning of the structure regardless of the kind of address being represented, an implementation which does not understand new address type X can still parse the IpAddressPort field and then discard it if it is not needed.

The rest of the IpAddressPort structure is either an IPv4AddrPort or an IPv6AddrPort. Both of these simply consist of an address represented as an integer and a 16-bit port. As an example, here is the wire representation of the IPv4 address "192.0.2.1" with port "6084".

```
01           ; type    = IPv4
06           ; length  = 6
c0 00 02 01  ; address = 192.0.2.1
17 c4        ; port    = 6084
```

Unless a given structure that uses a select explicitly allows for unknown types in the select, any unknown type SHOULD be treated as a parsing error, and the whole message SHOULD be discarded with no response.

6.3.2. Forwarding Header

The forwarding header is defined as a ForwardingHeader structure, as shown below.

```
struct {
  uint32             relo_token;
  uint32             overlay;
  uint16             configuration_sequence;
  uint8              version;
  uint8              ttl;
  uint32             fragment;
  uint32             length;
  uint64             transaction_id;
  uint32             max_response_length;
  uint16             via_list_length;
  uint16             destination_list_length;
  uint16             options_length;
  Destination        via_list[via_list_length];
  Destination        destination_list
                       [destination_list_length];
  ForwardingOption   options[options_length];
} ForwardingHeader;
```

The contents of the structure are:

relo_token: The first four bytes identify this message as a RELOAD message. This field MUST contain the value 0xd2454c4f (the string "RELO" with the high bit of the first byte set).

overlay: The 32-bit checksum/hash of the overlay being used. This MUST be formed by taking the lower 32 bits of the SHA-1 [RFC3174] hash of the overlay name. The purpose of this field is to allow nodes to participate in multiple overlays and to detect accidental misconfiguration. This is not a security-critical function. The overlay name MUST consist of a sequence of characters that would be allowable as a DNS name. Specifically, as it is used in a DNS lookup, it will need to be compliant with the grammar for the domain as specified in Section 2.3.1 of [RFC1035].

configuration_sequence: The sequence number of the configuration file. See Section 6.3.2.1 for details.

version: The version of the RELOAD protocol being used times 10. RELOAD version numbers are fixed-point decimal numbers between fixed-point integer between 0.1 and 25.4. This document describes version 1.0, with a value of 0x0a. (Note that versions used prior to the publication of this RFC used version number 0.1.) Nodes MUST reject messages with other versions.

ttl: An 8-bit field indicating the number of iterations, or hops, a message can experience before it is discarded. The TTL (time-to-live) value MUST be decremented by one at every hop along the route the message traverses just before transmission. If a received message has a TTL of 0 and the message is not destined for the receiving node, then the message MUST NOT be propagated further, and an Error_TTL_Exceeded error should be generated. The initial value of the TTL SHOULD be 100 and MUST NOT exceed 100 unless defined otherwise by the overlay configuration. Implementations which receive messages with a TTL greater than the current value of initial-ttl (or the default of 100) MUST discard the message and send an Error_TTL_Exceeded error.

fragment: This field is used to handle fragmentation. The high bit (0x80000000) MUST be set for historical reasons. If the next bit (0x40000000) is set to 1, it indicates that this is the last (or only) fragment. The next six bits (0x20000000 through 0x01000000) are reserved and SHOULD be set to zero. The remainder of the field is used to indicate the fragment offset; see Section 6.7 for details.

length: The count in bytes of the size of the message, including the header, after the eventual fragmentation.

transaction_id: A unique 64-bit number that identifies this transaction and also allows receivers to disambiguate transactions which are otherwise identical. In order to provide a high probability that transaction IDs are unique, they MUST be randomly generated. Responses use the same transaction ID as the request to which they correspond. Transaction IDs are also used for fragment reassembly. See Section 6.7 for details.

max_response_length: The maximum size in bytes of a response. This is used by requesting nodes to avoid receiving (unexpected) very large responses. If this value is non-zero, responding peers MUST check that any response would not exceed it and if so generate an Error_Incompatible_with_Overlay value. This value SHOULD be set to zero for responses.

via_list_length: The length of the Via List in bytes. Note that in this field and the following two length fields, we depart from the usual variable-length convention of having the length immediately precede the value, in order to make it easier for hardware decoding engines to quickly determine the length of the header.

destination_list_length: The length of the Destination List in bytes.

options_length: The length of the header options in bytes.

via_list: The via_list contains the sequence of destinations through which the message has passed. The via_list starts out empty and grows as the message traverses each peer. In stateless cases, the previous hop that the message is from is appended to the Via List as specified in Section 6.1.2.

destination_list: The destination_list contains a sequence of destinations through which the message should pass. The Destination List is constructed by the message originator. The first element on the Destination List is where the message goes next. Generally, the list shrinks as the message traverses each listed peer, though if list compression is used, this may not be true.

options: Contains a series of ForwardingOption entries. See Section 6.3.2.3.

6.3.2.1. Processing Configuration Sequence Numbers

In order to be part of the overlay, a node MUST have a copy of the overlay Configuration Document. In order to allow for configuration document changes, each version of the Configuration Document MUST contain a sequence number which MUST be monotonically increasing mod 65535. Because the sequence number may, in principle, wrap, greater than or less than are interpreted by modulo arithmetic as in TCP.

When a destination node receives a request, it MUST check that the configuration_sequence field is equal to its own configuration sequence number. If they do not match, the node MUST generate an error, either Error_Config_Too_Old or Error_Config_Too_New. In addition, if the configuration file in the request is too old, the node MUST generate a ConfigUpdate message to update the requesting node. This allows new Configuration Documents to propagate quickly throughout the system. The one exception to this rule is that if the configuration_sequence field is equal to 65535 and the message type is ConfigUpdate, then the message MUST be accepted regardless of the receiving node's configuration sequence number. Since 65535 is a special value, peers sending a new configuration when the configuration sequence is currently 65534 MUST set the configuration sequence number to 0 when they send a new configuration.

6.3.2.2. Destination and Via Lists

The Destination List and Via List are sequences of Destination values:

```
enum { invalidDestinationType(0), node(1), resource(2),
       opaque_id_type(3), /* 128-255 not allowed */ (255) }
     DestinationType;

select (destination_type) {
 case node:
        NodeId               node_id;

 case resource:
        ResourceId           resource_id;

 case opaque_id_type:
        opaque               opaque_id<0..2^8-1>;

     /* This structure may be extended with new types */
} DestinationData;

struct {
   DestinationType         type;
   uint8                   length;
   DestinationData         destination_data;
} Destination;

struct {
   uint16               opaque_id; /* Top bit MUST be 1 */
} Destination;
```

If the destination structure is a 16-bit integer, then the first bit MUST be set to 1, and it MUST be treated as if it were a full structure with a DestinationType of opaque_id_type and an opaque_id that was 2 bytes long with the value of the 16-bit integer. If the destination structure starts with DestinationType, then the first bit MUST be set to 0, and the destination structure must use a TLV structure with the following contents:

type
: The type of the DestinationData Payload Data Unit (PDU). It may be one of "node", "resource", or "opaque_id_type".

length
: The length of the destination_data.

destination_data
The destination value itself, which is an encoded DestinationData structure that depends on the value of "type".

Note that the destination structure encodes a Type, Length, Value. The Length field specifies the length of the DestinationData values, which allows the addition of new DestinationTypes. It also allows an implementation which does not understand a given DestinationType to skip over it.

A DestinationData can be one of three types:

node
A Node-ID.

opaque
A compressed list of Node-IDs and an eventual Resource-ID. Because this value has been compressed by one of the peers, it is meaningful only to that peer and cannot be decoded by other peers. Thus, it is represented as an opaque string.

resource
The Resource-ID of the resource which is desired. This type MUST appear only in the final location of a Destination List and MUST NOT appear in a Via List. It is meaningless to try to route through a resource.

One possible encoding of the 16-bit integer version as an opaque identifier is to encode an index into a Connection Table. To avoid misrouting responses in the event a response is delayed and the Connection Table entry has changed, the identifier SHOULD be split between an index and a generation counter for that index. When a Node first joins the overlay, the generation counters SHOULD be initialized to random values. An implementation MAY use 12 bits for the Connection Table index and 3 bits for the generation counter. (Note that this does not suggest a 4096-entry Connection Table for every peer, only the ability to encode for a larger Connection Table.) When a Connection Table slot is used for a new connection, the generation counter is incremented (with wrapping). Connection Table slots are used on a rotating basis to maximize the time interval between uses of the same slot for different connections. When routing a message to an entry in the Destination List encoding a Connection Table entry, the peer MUST confirm that the generation counter matches the current generation counter of that index before forwarding the message. If it does not match, the message MUST be silently dropped.

6.3.2.3. Forwarding Option

The Forwarding header can be extended with forwarding header options, which are a series of ForwardingOption structures:

```
 enum { invalidForwardingOptionType(0), (255) }
   ForwardingOptionType;

 struct {
   ForwardingOptionType      type;
   uint8                     flags;
   uint16                    length;
   select (type) {
         /* This type may be extended */
   };
 } ForwardingOption;
```

Each ForwardingOption consists of the following values:

type
: The type of the option. This structure allows for unknown options types.

flags
: Three flags are defined: FORWARD_CRITICAL(0x01), DESTINATION_CRITICAL(0x02), and RESPONSE_COPY(0x04). These flags MUST NOT be set in a response. If the FORWARD_CRITICAL flag is set, any peer that would forward the message but does not understand this option MUST reject the request with an Error_Unsupported_Forwarding_Option error response. If the DESTINATION_CRITICAL flag is set, any node that generates a response to the message but does not understand the forwarding option MUST reject the request with an Error_Unsupported_Forwarding_Option error response. If the RESPONSE_COPY flag is set, any node generating a response MUST copy the option from the request to the response except that the RESPONSE_COPY, FORWARD_CRITICAL, and DESTINATION_CRITICAL flags MUST be cleared.

length
: The length of the rest of the structure. Note that a 0 length may be reasonable if the mere presence of the option is meaningful and no value is required.

option
: The option value.

6.3.3. Message Contents Format

The second major part of a RELOAD message is the contents part, which is defined by MessageContents:

```
enum { invalidMessageExtensionType(0),
       (2^16-1) } MessageExtensionType;

struct {
  MessageExtensionType  type;
  Boolean               critical;
  opaque                extension_contents<0..2^32-1>;
} MessageExtension;

struct {
  uint16                 message_code;
  opaque                 message_body<0..2^32-1>;
  MessageExtension       extensions<0..2^32-1>;
} MessageContents;
```

The contents of this structure are as follows:

message_code
: This indicates the message that is being sent. The code space is broken up as follows:

  0x0 Invalid Message Code. This code will never be assigned.

  0x1 .. 0x7FFF Requests and responses. These code points are always paired, with requests being an odd value and the corresponding response being the request code plus 1. Thus, "probe_request" (the Probe request) has the value 1 and "probe_answer" (the Probe response) has the value 2

  0x8000 .. 0xFFFE Reserved

  0xFFFF Error

  The message codes are defined in Section 14.8.

message_body
: The message body itself, represented as a variable-length string of bytes. The bytes themselves are dependent on the code value. See the sections describing the various RELOAD methods (Join, Update, Attach, Store, Fetch, etc.) for the definitions of the payload contents.

extensions
Extensions to the message. Currently no extensions are defined, but new extensions can be defined by the process described in Section 14.14.

All extensions have the following form:

type
The extension type.

critical
Whether this extension needs to be understood in order to process the message. If critical = True and the recipient does not understand the message, it MUST generate an Error_Unknown_Extension error. If critical = False, the recipient MAY choose to process the message even if it does not understand the extension.

extension_contents
The contents of the extension (which are extension dependent).

The subsections 6.4.2, 6.5, and 7 describe structures that are inserted inside the message_body member, depending on the value of the message_code value. For example, a message_code value of join_req means that the structure named JoinReq is inserted inside message_body. This document does not contain a mapping between message_code values and structure names, as the conversion between the two is obvious.

Similarly, this document uses the name of the structure without the "Req" or "Ans" suffix to mean the execution of a transaction consisting of the matching request and answer. For example, when the text says "perform an Attach", it must be understood as performing a transaction composed of an AttachReq and an AttachAns.

6.3.3.1. Response Codes and Response Errors

A node processing a request MUST return its status in the message_code field. If the request was a success, then the message code MUST be set to the response code that matches the request (i.e., the next code up). The response payload is then as defined in the request/response descriptions.

If the request has failed, then the message code MUST be set to 0xffff (error) and the payload MUST be an error_response message, as shown below.

When the message code is 0xFFFF, the payload MUST be an ErrorResponse:

```
public struct {
  uint16             error_code;
  opaque             error_info<0..2^16-1>;
} ErrorResponse;
```

The contents of this structure are as follows:

error_code
: A numeric error code indicating the error that occurred.

error_info
: An optional arbitrary byte string. Unless otherwise specified, this will be a UTF-8 text string that provides further information about what went wrong. Developers are encouraged to include enough diagnostic information to be useful in error_info. The specific text to be used and any relevant language or encoding thereof is left to the implementation.

The following error code values are defined. The numeric values for these are defined in Section 14.9.

Error_Forbidden
: The requesting node does not have permission to make this request.

Error_Not_Found
: The resource or node cannot be found or does not exist.

Error_Request_Timeout
: A response to the request has not been received in a suitable amount of time. The requesting node MAY resend the request at a later time.

Error_Data_Too_Old
: A store cannot be completed because the storage_time precedes the existing value.

Error_Data_Too_Large
: A store cannot be completed because the requested object exceeds the size limits for that Kind.

Error_Generation_Counter_Too_Low
: A store cannot be completed because the generation counter precedes the existing value.

Error_Incompatible_with_Overlay
A peer receiving the request is using a different overlay, overlay algorithm, or hash algorithm, or some other parameter that is inconsistent with the overlay configuration.

Error_Unsupported_Forwarding_Option
A node received the request with a forwarding options flagged as critical, but the node does not support this option. See Section 6.3.2.3.

Error_TTL_Exceeded
A peer received the request in which the TTL was decremented to zero. See Section 6.3.2.

Error_Message_Too_Large
A peer received a request that was too large. See Section 6.6.

Error_Response_Too_Large
A node would have generated a response that is too large per the max_response_length field.

Error_Config_Too_Old
A destination node received a request with a configuration sequence that is too old. See Section 6.3.2.1.

Error_Config_Too_New
A destination node received a request with a configuration sequence that is too new. See Section 6.3.2.1.

Error_Unknown_Kind
A destination peer received a request with an unknown Kind-ID. See Section 7.4.1.2.

Error_In_Progress
An Attach to this peer is already in progress. See Section 6.5.1.2.

Error_Unknown_Extension
A destination node received a request with an unknown extension.

Error_Invalid_Message
Something about this message is invalid, but it does not fit the other error codes. When this message is sent, implementations SHOULD provide some meaningful description in error_info to aid in debugging.

Error_Exp_A
For the purposes of experimentation. It is not meant for vendor-specific use of any sort and MUST NOT be used for operational deployments.

Error_Exp_B
For the purposes of experimentation. It is not meant for vendor-specific use of any sort and MUST NOT be used for operational deployments.

6.3.4. Security Block

The third part of a RELOAD message is the security block. The security block is represented by a SecurityBlock structure:

```
struct {
   CertificateType     type;   // From RFC 6091
   opaque              certificate<0..2^16-1>;
} GenericCertificate;

struct {
   GenericCertificate certificates<0..2^16-1>;
   Signature          signature;
} SecurityBlock;
```

The contents of this structure are:

certificates
A bucket of certificates.

signature
A signature.

The certificates bucket SHOULD contain all the certificates necessary to verify every signature in both the message and the internal message objects, except for those certificates in a root-cert element of the current configuration file. This is the only location in the message which contains certificates, thus allowing only a single copy of each certificate to be sent. In systems that have an alternative certificate distribution mechanism, some certificates MAY be omitted. However, unless an alternative mechanism for immediately generating certificates, such as shared secret security (Section 13.4) is used, implementers MUST include all referenced certificates.

NOTE TO IMPLEMENTERS: This requirement implies that a peer storing data is obligated to retain certificates for the data that it holds.

Each certificate is represented by a GenericCertificate structure, which has the following contents:

type
The type of the certificate, as defined in [RFC6091]. Only the use of X.509 certificates is defined in this document.

certificate
The encoded version of the certificate. For X.509 certificates, it is the Distinguished Encoding Rules (DER) form.

The signature is computed over the payload and parts of the forwarding header. In case of a Store, the payload MUST contain an additional signature computed as described in Section 7.1. All signatures MUST be formatted using the Signature element. This element is also used in other contexts where signatures are needed. The input structure to the signature computation MAY vary depending on the data element being signed.

```
enum { invalidSignerIdentityType(0),
       cert_hash(1), cert_hash_node_id(2),
       none(3)
       (255) } SignerIdentityType;

struct {
  select (identity_type) {

    case cert_hash;
      HashAlgorithm      hash_alg;               // From TLS
      opaque             certificate_hash<0..2^8-1>;

    case cert_hash_node_id:
      HashAlgorithm      hash_alg;               // From TLS
      opaque             certificate_node_id_hash<0..2^8-1>;

    case none:
      /* empty */
    /* This structure may be extended with new types if necessary*/
  };
} SignerIdentityValue;

struct {
  SignerIdentityType     identity_type;
  uint16                 length;
  SignerIdentityValue    identity[SignerIdentity.length];
} SignerIdentity;
```

```
struct {
   SignatureAndHashAlgorithm     algorithm;   // From TLS
   SignerIdentity                identity;
   opaque                        signature_value<0..2^16-1>;
} Signature;
```

The Signature construct contains the following values:

algorithm
: The signature algorithm in use. The algorithm definitions are found in the IANA TLS SignatureAlgorithm and HashAlgorithm registries. All implementations MUST support RSASSA-PKCS1-v1_5 [RFC3447] signatures with SHA-256 hashes [RFC6234].

identity
: The identity, as defined in the two paragraphs following this list, used to form the signature.

signature_value
: The value of the signature.

  Note that storage operations allow for special values of algorithm and identity. See the Store Request definition (Section 7.4.1.1) and the Fetch Response definition (Section 7.4.2.2).

There are two permitted identity formats, one for a certificate with only one Node-ID and one for a certificate with multiple Node-IDs. In the first case, the cert_hash type MUST be used. The hash_alg field is used to indicate the algorithm used to produce the hash. The certificate_hash contains the hash of the certificate object (i.e., the DER-encoded certificate).

In the second case, the cert_hash_node_id type MUST be used. The hash_alg is as in cert_hash, but the cert_hash_node_id is computed over the NodeId used to sign concatenated with the certificate; i.e., H(NodeId || certificate). The NodeId is represented without any framing or length fields, as simple raw bytes. This is safe because NodeIds are a fixed length for a given overlay.

For signatures over messages, the input to the signature is computed over:

  overlay || transaction_id || MessageContents || SignerIdentity

where overlay and transaction_id come from the forwarding header and || indicates concatenation.

The input to signatures over data values is different and is described in Section 7.1.

All RELOAD messages MUST be signed. Intermediate nodes do not verify signatures. Upon receipt (and fragment reassembly, if needed), the destination node MUST verify the signature and the authorizing certificate. If the signature fails, the implementation SHOULD simply drop the message and MUST NOT process it. This check provides a minimal level of assurance that the sending node is a valid part of the overlay, and it provides cryptographic authentication of the sending node. In addition, responses MUST be checked as follows by the requesting node:

1. The response to a message sent to a Node-ID MUST have been sent by that Node-ID unless the response has been sent to the wildcard Node-ID.

2. The response to a message sent to a Resource-ID MUST have been sent by a Node-ID which is at least as close to the target Resource-ID as any node in the requesting node's Neighbor Table.

The second condition serves as a primitive check for responses from wildly wrong nodes but is not a complete check. Note that in periods of churn, it is possible for the requesting node to obtain a closer neighbor while the request is outstanding. This will cause the response to be rejected and the request to be retransmitted.

In addition, some methods (especially Store) have additional authentication requirements, which are described in the sections covering those methods.

6.4. Overlay Topology

As discussed in previous sections, RELOAD defines a default overlay topology (CHORD-RELOAD) but allows for other topologies through the use of Topology Plug-ins. This section describes the requirements for new Topology Plug-ins and the methods that RELOAD provides for overlay topology maintenance.

6.4.1. Topology Plug-in Requirements

When specifying a new overlay algorithm, at least the following MUST be described:

- Joining procedures, including the contents of the Join message.

- Stabilization procedures, including the contents of the Update message, the frequency of topology probes and keepalives, and the mechanism used to detect when peers have disconnected.
- Exit procedures, including the contents of the Leave message.
- The length of the Resource-IDs and for DHTs the hash algorithm to compute the hash of an identifier.
- The procedures that peers use to route messages.
- The replication strategy used to ensure data redundancy.

All overlay algorithms MUST specify maintenance procedures that send Updates to clients and peers that have established connections to the peer responsible for a particular ID when the responsibility for that ID changes. Because tracking this information is difficult, overlay algorithms MAY simply specify that an Update is sent to all members of the Connection Table whenever the range of IDs for which the peer is responsible changes.

6.4.2. Methods and Types for Use by Topology Plug-ins

This section describes the methods that Topology Plug-ins use to join, leave, and maintain the overlay.

6.4.2.1. Join

A new peer (which already has credentials) uses the JoinReq message to join the overlay. The JoinReq is sent to the responsible peer depending on the routing mechanism described in the Topology Plug-in. This message notifies the responsible peer that the new peer is taking over some of the overlay and that it needs to synchronize its state.

```
struct {
   NodeId                joining_peer_id;
   opaque                overlay_specific_data<0..2^16-1>;
} JoinReq;
```

The minimal JoinReq contains only the Node-ID which the sending peer wishes to assume. Overlay algorithms MAY specify other data to appear in this request. Receivers of the JoinReq MUST verify that the joining_peer_id field matches the Node-ID used to sign the message and, if not, the message MUST be rejected with an Error_Forbidden error.

Because joins may be executed only between nodes which are directly adjacent, receiving peers MUST verify that any JoinReq they receive arrives from a transport channel that is bound to the Node-ID to be assumed by the Joining Node. Implementations MUST use DTLS anti-replay mechanisms, thus preventing replay attacks.

If the request succeeds, the responding peer responds with a JoinAns message, as defined below:

```
struct {
   opaque                overlay_specific_data<0..2^16-1>;
} JoinAns;
```

If the request succeeds, the responding peer MUST follow up by executing the right sequence of Stores and Updates to transfer the appropriate section of the overlay space to the Joining Node. In addition, overlay algorithms MAY define data to appear in the response payload that provides additional information.

Joining Nodes MUST verify that the signature on the JoinAns message matches the expected target (i.e., the adjacency over which they are joining). If not, they MUST discard the message.

In general, nodes which cannot form connections SHOULD report an error to the user. However, implementations MUST provide some mechanism whereby nodes can determine that they are potentially the first node and can take responsibility for the overlay. (The idea is to avoid having ordinary nodes try to become responsible for the entire overlay during a partition.) This specification does not mandate any particular mechanism, but a configuration flag or setting seems appropriate.

6.4.2.2. Leave

The LeaveReq message is used to indicate that a node is exiting the overlay. A node SHOULD send this message to each peer with which it is directly connected prior to exiting the overlay.

```
struct {
   NodeId                leaving_peer_id;
   opaque                overlay_specific_data<0..2^16-1>;
} LeaveReq;
```

LeaveReq contains only the Node-ID of the leaving peer. Overlay algorithms MAY specify other data to appear in this request. Receivers of the LeaveReq MUST verify that the leaving_peer_id field matches the Node-ID used to sign the message and, if not, the message MUST be rejected with an Error_Forbidden error.

Because leaves may be executed only between nodes which are directly adjacent, receiving peers MUST verify that any LeaveReq they receive arrives from a transport channel that is bound to the Node-ID to be assumed by the leaving peer. This also prevents replay attacks, provided that DTLS anti-replay is used.

Upon receiving a Leave request, a peer MUST update its own Routing Table and send the appropriate Store/Update sequences to re-stabilize the overlay.

LeaveAns is an empty message.

6.4.2.3. Update

Update is the primary overlay-specific maintenance message. It is used by the sender to notify the recipient of the sender's view of the current state of the overlay (that is, its routing state), and it is up to the recipient to take whatever actions are appropriate to deal with the state change. In general, peers send Update messages to all their adjacencies whenever they detect a topology shift.

When a peer receives an Attach request with the send_update flag set to True (Section 6.4.2.4.1), it MUST send an Update message back to the sender of the Attach request after completion of the corresponding ICE check and TLS connection. Note that the sender of such an Attach request may not have joined the overlay yet.

When a peer detects through an Update that it is no longer responsible for any data value it is storing, it MUST attempt to Store a copy to the correct node unless it knows the newly responsible node already has a copy of the data. This prevents data loss during large-scale topology shifts, such as the merging of partitioned overlays.

The contents of the UpdateReq message are completely overlay specific. The UpdateAns response is expected to be either success or an error.

6.4.2.4. RouteQuery

The RouteQuery request allows the sender to ask a peer where they would route a message directed to a given destination. In other words, a RouteQuery for a destination X requests the Node-ID for the node that the receiving peer would next route to in order to get to X. A RouteQuery can also request that the receiving peer initiate an Update request to transfer the receiving peer's Routing Table.

One important use of the RouteQuery request is to support iterative routing. The sender selects one of the peers in its Routing Table and sends it a RouteQuery message with the destination field set to the Node-ID or Resource-ID to which it wishes to route. The receiving peer responds with information about the peers to which the request would be routed. The sending peer MAY then use the Attach method to attach to that peer(s) and repeat the RouteQuery. Eventually, the sender gets a response from a peer that is closest to the identifier in the destination field as determined by the Topology Plug-in. At that point, the sender can send messages directly to that peer.

6.4.2.4.1. Request Definition

A RouteQueryReq message indicates the peer or resource that the requesting node is interested in. It also contains a "send_update" option that allows the requesting node to request a full copy of the other peer's Routing Table.

```
struct {
  Boolean                send_update;
  Destination            destination;
  opaque                 overlay_specific_data<0..2^16-1>;
} RouteQueryReq;
```

The contents of the RouteQueryReq message are as follows:

send_update
: A single byte. This may be set to True to indicate that the requester wishes the responder to initiate an Update request immediately. Otherwise, this value MUST be set to False.

destination
: The destination which the requester is interested in. This may be any valid destination object, including a Node-ID, opaque ID, or Resource-ID.
Note: If implementations are using opaque IDs for privacy purposes, answering RouteQueryReqs for opaque IDs will allow the requester to translate an opaque ID. Implementations MAY wish to consider limiting the use of RouteQuery for opaque IDs in such cases.

overlay_specific_data
: Other data as appropriate for the overlay.

6.4.2.4.2. Response Definition

A response to a successful RouteQueryReq request is a RouteQueryAns message. This message is completely overlay specific.

6.4.2.5. Probe

Probe provides primitive "exploration" services: it allows a node to determine which resources another node is responsible for. A probe can be addressed to a specific Node-ID or to the peer controlling a given location (by using a Resource-ID). In either case, the target node responds with a simple response containing some status information.

6.4.2.5.1. Request Definition

The ProbeReq message contains a list (potentially empty) of the pieces of status information that the requester would like the responder to provide.

```
enum { invalidProbeInformationType(0), responsible_set(1),
       num_resources(2), uptime(3), (255) }
     ProbeInformationType;

struct {
  ProbeInformationType     requested_info<0..2^8-1>;
} ProbeReq;
```

The currently defined values for ProbeInformationType are:

responsible_set
: Indicates that the peer should Respond with the fraction of the overlay for which the responding peer is responsible.

num_resources
: Indicates that the peer should Respond with the number of resources currently being stored by the peer. Note that multiple values under the same Resource-ID are counted only once.

uptime
: Indicates that the peer should Respond with how long the peer has been up, in seconds.

6.4.2.5.2. Response Definition

A successful ProbeAns response contains the information elements requested by the peer.

```
      struct {
        select (type) {
          case responsible_set:
            uint32              responsible_ppb;

          case num_resources:
            uint32              num_resources;

          case uptime:
            uint32              uptime;

          /* This type may be extended */
        };
      } ProbeInformationData;

      struct {
        ProbeInformationType    type;
        uint8                   length;
        ProbeInformationData    value;
      } ProbeInformation;

      struct {
        ProbeInformation        probe_info<0..2^16-1>;
      } ProbeAns;
```

A ProbeAns message contains a sequence of ProbeInformation structures. Each has a "length" indicating the length of the following value field. This structure allows for unknown option types.

Each of the current possible Probe information types is a 32-bit unsigned integer. For type "responsible_ppb", it is the fraction of the overlay for which the peer is responsible, in parts per billion. For type "num_resources", it is the number of resources the peer is storing. For the type "uptime", it is the number of seconds the peer has been up.

The responding peer SHOULD include any values that the requesting node requested and that it recognizes. They SHOULD be returned in the requested order. Any other values MUST NOT be returned.

6.5. Forwarding and Link Management Layer

Each node maintains connections to a set of other nodes defined by the Topology Plug-in. This section defines the methods RELOAD uses to form and maintain connections between nodes in the overlay. Three methods are defined:

Attach
: Used to form RELOAD connections between nodes using ICE for NAT traversal. When node A wants to connect to node B, it sends an Attach message to node B through the overlay. The Attach contains A's ICE parameters. B responds with its ICE parameters, and the two nodes perform ICE to form connection. Attach also allows two nodes to connect via No-ICE instead of full ICE.

AppAttach
: Used to form application-layer connections between nodes.

Ping
: A simple request/response which is used to verify connectivity of the target peer.

6.5.1. Attach

A node sends an Attach request when it wishes to establish a direct Overlay Link connection to another node for the purpose of sending RELOAD messages. A client that can establish a connection directly need not send an Attach, as described in the second bullet of Section 4.2.1.

As described in Section 6.1, an Attach may be routed to either a Node-ID or a Resource-ID. An Attach routed to a specific Node-ID will fail if that node is not reached. An Attach routed to a Resource-ID will establish a connection with the peer currently responsible for that Resource-ID, which may be useful in establishing a direct connection to the responsible peer for use with frequent or large resource updates.

An Attach, in and of itself, does not result in updating the Routing Table of either node. That function is performed by Updates. If node A has Attached to node B, but has not received any Updates from B, it MAY route messages which are directly addressed to B through that channel, but it MUST NOT route messages through B to other peers via that channel. The process of Attaching is separate from the process of becoming a peer (using Join and Update), to prevent half-open states where a node has started to form connections but is not really ready to act as a peer. Thus, clients (unlike peers) can simply Attach without sending Join or Update.

6.5.1.1. Request Definition

An Attach request message contains the requesting node ICE connection parameters formatted into a binary structure.

```
enum { invalidOverlayLinkType(0), DTLS-UDP-SR(1),
       DTLS-UDP-SR-NO-ICE(3), TLS-TCP-FH-NO-ICE(4),
       (255) } OverlayLinkType;

enum { invalidCandType(0),
       host(1), srflx(2), /* RESERVED(3), */ relay(4),
       (255) } CandType;

struct {
  opaque                name<0..2^16-1>;
  opaque                value<0..2^16-1>;
} IceExtension;

struct {
  IpAddressPort         addr_port;
  OverlayLinkType       overlay_link;
  opaque                foundation<0..255>;
  uint32                priority;
  CandType              type;
  select (type) {
    case host:
      ;           /* Empty */
    case srflx:
    case relay:
      IpAddressPort     rel_addr_port;
  };
  IceExtension          extensions<0..2^16-1>;
} IceCandidate;

struct {
  opaque                ufrag<0..2^8-1>;
  opaque                password<0..2^8-1>;
  opaque                role<0..2^8-1>;
  IceCandidate          candidates<0..2^16-1>;
  Boolean               send_update;
} AttachReqAns;
```

The values contained in AttachReqAns are:

ufrag
: The username fragment (from ICE).

password
The ICE password.

role
An active/passive/actpass attribute from RFC 4145 [RFC4145]. This value MUST be "passive" for the offerer (the peer sending the Attach request) and "active" for the answerer (the peer sending the Attach response).

candidates
One or more ICE candidate values, as described below.

send_update
Has the same meaning as the send_update field in RouteQueryReq.

Each ICE candidate is represented as an IceCandidate structure, which is a direct translation of the information from the ICE string structures, with the exception of the component ID. Since there is only one component, it is always 1, and thus left out of the structure. The remaining values are specified as follows:

addr_port
Corresponds to the ICE connection-address and port productions.

overlay_link
Corresponds to the ICE transport production. Overlay Link protocols used with No-ICE MUST specify "No-ICE" in their description. Future overlay link values can be added by defining new OverlayLinkType values in the IANA registry as described in Section 14.10. Future extensions to the encapsulation or framing that provide for backward compatibility with the previously specified encapsulation or framing values MUST use the same OverlayLinkType value that was previously defined. OverlayLinkType protocols are defined in Section 6.6

A single AttachReqAns MUST NOT include both candidates whose OverlayLinkType protocols use ICE (the default) and candidates that specify "No-ICE".

foundation
Corresponds to the ICE foundation production.

priority
Corresponds to the ICE priority production.

type
Corresponds to the ICE cand-type production.

rel_addr_port
Corresponds to the ICE rel-addr and rel-port productions. It is present only for types "relay", "prfix", and "srflx".

extensions
ICE extensions. The name and value fields correspond to binary translations of the equivalent fields in the ICE extensions.

These values should be generated using the procedures described in Section 6.5.1.3.

6.5.1.2. Response Definition

If a peer receives an Attach request, it MUST determine how to process the request as follows:

- If the peer has not initiated an Attach request to the originating peer of this Attach request, it MUST process this request and SHOULD generate its own response with an AttachReqAns. It should then begin ICE checks.
- If the peer has already sent an Attach request to and received the response from the originating peer of this Attach request and, as a result, an ICE check and TLS connection are in progress, then it SHOULD generate an Error_In_Progress error instead of an AttachReqAns.
- If the peer has already sent an Attach request to but not yet received the response from the originating peer of this Attach request, it SHOULD apply the following tie-breaker heuristic to determine how to handle this Attach request and the incomplete Attach request it has sent out:
  - If the peer's own Node-ID is smaller when compared as big-endian unsigned integers, it MUST cancel retransmission of its own incomplete Attach request. It MUST then process this Attach request, generate an AttachReqAns response, and proceed with the corresponding ICE check.
  - If the peer's own Node-ID is larger when compared as big-endian unsigned integers, it MUST generate an Error_In_Progress error to this Attach request, and then proceed to wait for and complete the Attach and the corresponding ICE check it has originated.
- If the peer is overloaded or detects some other kind of error, it MAY generate an error instead of an AttachReqAns.

When a peer receives an Attach response, it SHOULD parse the response and begin its own ICE checks.

6.5.1.3. Using ICE with RELOAD

This section describes the profile of ICE that is used with RELOAD. RELOAD implementations MUST implement full ICE.

In ICE, as defined by [RFC5245], the Session Description Protocol (SDP) is used to carry the ICE parameters. In RELOAD, this function is performed by a binary encoding in the Attach method. This encoding is more restricted than the SDP encoding because the RELOAD environment is simpler:

- Only a single media stream is supported.
- In this case, the "stream" refers not to RTP or other types of media, but rather to a connection for RELOAD itself or other application-layer protocols, such as SIP.
- RELOAD allows only for a single offer/answer exchange. Unlike the usage of ICE within SIP, there is never a need to send a subsequent offer to update the default candidates to match the ones selected by ICE.

An agent follows the ICE specification as described in [RFC5245] with the changes and additional procedures described in the subsections below.

6.5.1.4. Collecting STUN Servers

ICE relies on the node having one or more Session Traversal Utilities for NAT (STUN) servers to use. In conventional ICE, it is assumed that nodes are configured with one or more STUN servers through some out-of-band mechanism. This is still possible in RELOAD, but RELOAD also learns STUN servers as it connects to other peers.

A peer on a well-provisioned wide-area overlay will be configured with one or more bootstrap nodes. These nodes make an initial list of STUN servers. However, as the peer forms connections with additional peers, it builds more peers that it can use like STUN servers.

Because complicated NAT topologies are possible, a peer may need more than one STUN server. Specifically, a peer that is behind a single NAT will typically observe only two IP addresses in its STUN checks: its local address and its server reflexive address from a STUN server outside its NAT. However, if more NATs are involved, a peer may

learn additional server reflexive addresses (which vary based on where in the topology the STUN server is). To maximize the chance of achieving a direct connection, a peer SHOULD group other peers by the peer-reflexive addresses it discovers through them. It SHOULD then select one peer from each group to use as a STUN server for future connections.

Only peers to which the peer currently has connections may be used. If the connection to that host is lost, it MUST be removed from the list of STUN servers, and a new server from the same group MUST be selected unless there are no others servers in the group, in which case some other peer MAY be used.

6.5.1.5. Gathering Candidates

When a node wishes to establish a connection for the purposes of RELOAD signaling or application signaling, it follows the process of gathering candidates as described in Section 4 of ICE [RFC5245]. RELOAD utilizes a single component. Consequently, gathering for these "streams" requires a single component. In the case where a node has not yet found a TURN server, the agent would not include a relayed candidate.

The ICE specification assumes that an ICE agent is configured with, or somehow knows of, TURN and STUN servers. RELOAD provides a way for an agent to learn these by querying the overlay, as described in Sections 6.5.1.4 and 9.

The default candidate selection described in Section 4.1.4 of ICE is ignored; defaults are not signaled or utilized by RELOAD.

An alternative to using the full ICE supported by the Attach request is to use the No-ICE mechanism by providing candidates with "No-ICE" Overlay Link protocols. Configuration for the overlay indicates whether or not these Overlay Link protocols can be used. An overlay MUST be either all ICE or all No-ICE.

No-ICE will not work in all the scenarios where ICE would work, but in some cases, particularly those with no NATs or firewalls, it will work.

6.5.1.6. Prioritizing Candidates

Standardization of additional protocols for use with ICE is expected, including TCP [RFC6544] and protocols such as the Stream Control Transmission Protocol (SCTP) [RFC4960] and Datagram Congestion Control Protocol (DCCP) [RFC4340]. UDP encapsulations for SCTP and DCCP would expand the Overlay Link protocols available for RELOAD.

When additional protocols are available, the following prioritization is RECOMMENDED:

- Highest priority is assigned to protocols that offer well-understood congestion and flow control without head-of-line blocking, for example, SCTP without message ordering, DCCP, and those protocols encapsulated using UDP.

- Second highest priority is assigned to protocols that offer well-understood congestion and flow control, but that have head-of-line blocking, such as TCP.

- Lowest priority is assigned to protocols encapsulated over UDP that do not implement well-established congestion control algorithms. The DTLS/UDP with Simple Reliability (SR) overlay link protocol is an example of such a protocol.

Head-of-line blocking is undesirable in an Overlay Link protocol, because the messages carried on a RELOAD link are independent, rather than stream-oriented. Therefore, if message N on a link is lost, delaying message N+1 on that same link until N is successfully retransmitted does nothing other than increase the latency for the transaction of message N+1, as they are unrelated to each other. Therefore, while the high quality, performance, and availability of modern TCP implementations makes them very attractive, their performance as Overlay Link protocols is not optimal.

Note that none of the protocols defined in this document meets these conditions, but it is expected that new Overlay Link protocols defined in the future will fill this gap.

6.5.1.7. Encoding the Attach Message

Section 4.3 of ICE describes procedures for encoding the SDP for conveying RELOAD candidates. Instead of actually encoding an SDP message, the candidate information (IP address and port and transport protocol, priority, foundation, type, and related address) is carried within the attributes of the Attach request or its response. Similarly, the username fragment and password are carried in the Attach message or its response. Section 6.5.1 describes the detailed attribute encoding for Attach. The Attach request and its response do not contain any default candidates or the ice-lite attribute, as these features of ICE are not used by RELOAD.

Since the Attach request contains the candidate information and short term credentials, it is considered as an offer for a single media stream that happens to be encoded in a format different than SDP, but is otherwise considered a valid offer for the purposes of following

the ICE specification. Similarly, the Attach response is considered a valid answer for the purposes of following the ICE specification.

6.5.1.8. Verifying ICE Support

An agent MUST skip the verification procedures in Sections 5.1 and 6.1 of ICE. Since RELOAD requires full ICE from all agents, this check is not required.

6.5.1.9. Role Determination

The roles of controlling and controlled, as described in Section 5.2 of ICE, are still utilized with RELOAD. However, the offerer (the entity sending the Attach request) will always be controlling, and the answerer (the entity sending the Attach response) will always be controlled. The connectivity checks MUST still contain the ICE-CONTROLLED and ICE-CONTROLLING attributes, however, even though the role reversal capability for which they are defined will never be needed with RELOAD. This is to allow for a common codebase between ICE for RELOAD and ICE for SDP.

6.5.1.10. Full ICE

When the overlay uses ICE, connectivity checks and nominations are used as in regular ICE.

6.5.1.10.1. Connectivity Checks

The processes of forming check lists in Section 5.7 of ICE, scheduling checks in Section 5.8, and checking connectivity checks in Section 7 are used with RELOAD without change.

6.5.1.10.2. Concluding ICE

The procedures in Section 8 of ICE are followed to conclude ICE, with the following exceptions:

- The controlling agent MUST NOT attempt to send an updated offer once the state of its single media stream reaches Completed.
- Once the state of ICE reaches Completed, the agent can immediately free all unused candidates. This is because RELOAD does not have the concept of forking, and thus the three-second delay in Section 8.3 of ICE does not apply.

6.5.1.10.3. Media Keepalives

STUN MUST be utilized for the keepalives described in Section 10 of ICE.

6.5.1.11. No-ICE

No-ICE is selected when either side has provided "no ICE" Overlay Link candidates. STUN is not used for connectivity checks when doing No-ICE; instead, the DTLS or TLS handshake (or similar security layer of future overlay link protocols) forms the connectivity check. The certificate exchanged during the TLS or DTLS handshake MUST match the node which sent the AttachReqAns, and if it does not, the connection MUST be closed.

6.5.1.12. Subsequent Offers and Answers

An agent MUST NOT send a subsequent offer or answer. Thus, the procedures in Section 9 of ICE MUST be ignored.

6.5.1.13. Sending Media

The procedures of Section 11 of ICE apply to RELOAD as well. However, in this case, the "media" takes the form of application-layer protocols (e.g., RELOAD) over TLS or DTLS. Consequently, once ICE processing completes, the agent will begin TLS or DTLS procedures to establish a secure connection. The node that sent the Attach request MUST be the TLS server. The other node MUST be the TLS client. The server MUST request TLS client authentication. The nodes MUST verify that the certificate presented in the handshake matches the identity of the other peer as found in the Attach message. Once the TLS or DTLS signaling is complete, the application protocol is free to use the connection.

The concept of a previous selected pair for a component does not apply to RELOAD, since ICE restarts are not possible with RELOAD.

6.5.1.14. Receiving Media

An agent MUST be prepared to receive packets for the application protocol (TLS or DTLS carrying RELOAD) at any time. The jitter and RTP considerations in Section 11 of ICE do not apply to RELOAD.

6.5.2. AppAttach

A node sends an AppAttach request when it wishes to establish a direct connection to another node for the purposes of sending application-layer messages. AppAttach is nearly identical to Attach,

except for the purpose of the connection: it is used to transport non-RELOAD "media". A separate request is used to avoid implementer confusion between the two methods (this was found to be a real problem with initial implementations). The AppAttach request and its response contain an application attribute, which indicates what protocol is to be run over the connection.

6.5.2.1. Request Definition

An AppAttachReq message contains the requesting node's ICE connection parameters formatted into a binary structure.

```
struct {
  opaque                ufrag<0..2^8-1>;
  opaque                password<0..2^8-1>;
  uint16                application;
  opaque                role<0..2^8-1>;
  IceCandidate          candidates<0..2^16-1>;
} AppAttachReq;
```

The values contained in AppAttachReq and AppAttachAns are:

ufrag
: The username fragment (from ICE).

password
: The ICE password.

application
: A 16-bit Application-ID, as defined in the Section 14.5. This number represents the IANA-registered application that is going to send data on this connection.

role
: An active/passive/actpass attribute from RFC 4145 [RFC4145].

candidates
: One or more ICE candidate values.

The application using the connection that is set up with this request is responsible for providing traffic of sufficient frequency to keep the NAT and Firewall binding alive. Applications will often send traffic every 25 seconds to ensure this.

6.5.2.2. Response Definition

If a peer receives an AppAttach request, it SHOULD process the request and generate its own response with a AppAttachAns. It should then begin ICE checks. When a peer receives an AppAttach response, it SHOULD parse the response and begin its own ICE checks. If the Application ID is not supported, the peer MUST reply with an Error_Not_Found error.

```
struct {
  opaque                  ufrag<0..2^8-1>;
  opaque                  password<0..2^8-1>;
  uint16                  application;
  opaque                  role<0..2^8-1>;
  IceCandidate            candidates<0..2^16-1>;
} AppAttachAns;
```

The meaning of the fields is the same as in the AppAttachReq.

6.5.3. Ping

Ping is used to test connectivity along a path. A ping can be addressed to a specific Node-ID, to the peer controlling a given location (by using a Resource-ID), or to the wildcard Node-ID.

6.5.3.1. Request Definition

The PingReq structure is used to make a Ping request.

```
struct {
  opaque<0..2^16-1> padding;
} PingReq;
```

The Ping request is empty of meaningful contents. However, it may contain up to 65535 bytes of padding to facilitate the discovery of overlay maximum packet sizes.

6.5.3.2. Response Definition

A successful PingAns response contains the information elements requested by the peer.

```
struct {
  uint64                  response_id;
  uint64                  time;
} PingAns;
```

A PingAns message contains the following elements:

response_id
: A randomly generated 64-bit response ID. This is used to distinguish Ping responses.

time
: The time when the Ping response was created, represented in the same way as storage_time, defined in Section 7.

6.5.4. ConfigUpdate

The ConfigUpdate method is used to push updated configuration data across the overlay. Whenever a node detects that another node has old configuration data, it MUST generate a ConfigUpdate request. The ConfigUpdate request allows updating of two kinds of data: the configuration data (Section 6.3.2.1) and the Kind information (Section 7.4.1.1).

6.5.4.1. Request Definition

The ConfigUpdateReq structure is used to provide updated configuration information.

```
enum { invalidConfigUpdateType(0), config(1), kind(2), (255) }
     ConfigUpdateType;

typedef uint32           KindId;
typedef opaque           KindDescription<0..2^16-1>;

struct {
  ConfigUpdateType       type;
  uint32                 length;

  select (type) {
    case config:
                opaque             config_data<0..2^24-1>;

    case kind:
                KindDescription    kinds<0..2^24-1>;

    /* This structure may be extended with new types */
  };
} ConfigUpdateReq;
```

The ConfigUpdateReq message contains the following elements:

type
The type of the contents of the message. This structure allows for unknown content types.

length
The length of the remainder of the message. This is included to preserve backward compatibility and is 32 bits instead of 24 to facilitate easy conversion between network and host byte order.

config_data (type==config)
The contents of the Configuration Document.

kinds (type==kind)
One or more XML kind-block productions (see Section 11.1). These MUST be encoded with UTF-8 and assume a default namespace of "urn:ietf:params:xml:ns:p2p:config-base".

6.5.4.2. Response Definition

The ConfigUpdateAns structure is used to respond to a ConfigUpdateReq request.

```
struct {
} ConfigUpdateAns;
```

If the ConfigUpdateReq is of type "config", it MUST be processed only if all the following are true:

- The sequence number in the document is greater than the current configuration sequence number.
- The Configuration Document is correctly digitally signed (see Section 11 for details on signatures).

Otherwise, appropriate errors MUST be generated.

If the ConfigUpdateReq is of type "kind", it MUST be processed only if it is correctly digitally signed by an acceptable Kind signer (i.e., one listed in the current configuration file). Details on the kind-signer field in the configuration file are described in Section 11.1. In addition, if the Kind update conflicts with an existing known Kind (i.e., it is signed by a different signer), then it should be rejected with an Error_Forbidden error. This should not happen in correctly functioning overlays.

If the update is acceptable, then the node MUST reconfigure itself to match the new information. This may include adding permissions for new Kinds, deleting old Kinds, or even, in extreme circumstances, exiting and re-entering the overlay, if, for instance, the DHT algorithm has changed.

If an implementation misses enough ConfigUpdates that include key changes, it is possible that it will no longer be able to verify new valid ConfigUpdates. In this case, the only available recovery mechanism is to attempt to retrieve a new Configuration Document, typically by the mechanisms used for initial bootstrapping. It is up to implementers whether or how to decide to employ this sort of recovery mechanism.

The response for ConfigUpdate is empty.

6.6. Overlay Link Layer

RELOAD can use multiple Overlay Link protocols to send its messages. Because ICE is used to establish connections (see Section 6.5.1.3), RELOAD nodes are able to detect which Overlay Link protocols are offered by other nodes and establish connections between them. Any link protocol needs to be able to establish a secure, authenticated connection and to provide data origin authentication and message integrity for individual data elements. RELOAD currently supports three Overlay Link protocols:

- DTLS [RFC6347] over UDP with Simple Reliability (SR) (OverlayLinkType=DTLS-UDP-SR)
- TLS [RFC5246] over TCP with Framing Header, No-ICE (OverlayLinkType=TLS-TCP-FH-NO-ICE)
- DTLS [RFC6347] over UDP with SR, No-ICE (OverlayLinkType=DTLS-UDP-SR-NO-ICE)

Note that although UDP does not properly have "connections", both TLS and DTLS have a handshake that establishes a similar, stateful association. We refer to these as "connections" for the purposes of this document.

If a peer receives a message that is larger than the value of max-message-size defined in the overlay configuration, the peer SHOULD send an Error_Message_Too_Large error and then close the TLS or DTLS session from which the message was received. Note that this error can be sent and the session closed before the peer receives the complete message. If the forwarding header is larger than the max-

message-size, the receiver SHOULD close the TLS or DTLS session without sending an error.

The RELOAD mechanism requires that failed links be quickly removed from the Routing Table so end-to-end retransmission can handle lost messages. Overlay Link protocols MUST be designed with a mechanism that quickly signals a likely failure, and implementations SHOULD quickly act to remove a failed link from the Routing Table when receiving this signal. The entry can be restored if it proves to resume functioning, or it can be replaced at some point in the future if necessary. Section 10.7.2 contains more details specific to the CHORD-RELOAD Topology Plug-in.

The Framing Header (FH) is used to frame messages and provide timing when used on a reliable stream-based transport protocol. Simple Reliability (SR) uses the FH to provide congestion control and partial reliability when using unreliable message-oriented transport protocols. We will first define each of these algorithms in Sections 6.6.2 and 6.6.3, and then define Overlay Link protocols that use them in Sections 6.6.4, 6.6.5, and 6.6.6.

Note: We expect future Overlay Link protocols to define replacements for all components of these protocols, including the Framing Header. The three protocols that we will discuss have been chosen for simplicity of implementation and reasonable performance.

6.6.1. Future Overlay Link Protocols

It is possible to define new link-layer protocols and apply them to a new overlay using the "overlay-link-protocol" configuration directive (see Section 11.1.). However, any new protocols MUST meet the following requirements:

Endpoint authentication: When a node forms an association with another endpoint, it MUST be possible to cryptographically verify that the endpoint has a given Node-ID.

Traffic origin authentication and integrity: When a node receives traffic from another endpoint, it MUST be possible to cryptographically verify that the traffic came from a given association and that it has not been modified in transit from the other endpoint in the association. The overlay link protocol MUST also provide replay prevention/detection.

Traffic confidentiality: When a node sends traffic to another endpoint, it MUST NOT be possible for a third party that is not involved in the association to determine the contents of that traffic.

Any new overlay protocol MUST be defined via Standards Action [RFC5226]. See Section 14.11.

6.6.1.1. HIP

In a Host Identity Protocol Based Overlay Networking Environment (HIP BONE) [RFC6079], HIP [RFC5201] provides connection management (e.g., NAT traversal and mobility) and security for the overlay network. The P2PSIP Working Group has expressed interest in supporting a HIP-based link protocol. Such support would require specifying such details as:

- How to issue certificates which provide identities meaningful to the HIP base exchange. We anticipate that this would require a mapping between Overlay Routable Cryptographic Hash Identifiers (ORCHIDs) and NodeIds.
- How to carry the HIP I1 and I2 messages.
- How to carry RELOAD messages over HIP.

[HIP-RELOAD] documents work in progress on using RELOAD with the HIP BONE.

6.6.1.2. ICE-TCP

The ICE-TCP RFC [RFC6544] allows TCP to be supported as an Overlay Link protocol that can be added using ICE.

6.6.1.3. Message-Oriented Transports

Modern message-oriented transports offer high performance and good congestion control, and they avoid head-of-line blocking in case of lost data. These characteristics make them preferable as underlying transport protocols for RELOAD links. SCTP without message ordering and DCCP are two examples of such protocols. However, currently they are not well-supported by commonly available NATs, and specifications for ICE session establishment are not available.

6.6.1.4. Tunneled Transports

As of the time of this writing, there is significant interest in the IETF community in tunneling other transports over UDP, which is motivated by the situation that UDP is well-supported by modern NAT hardware and by the fact that performance similar to a native implementation can be achieved. Currently, SCTP, DCCP, and a generic tunneling extension are being proposed for message-oriented protocols. Once ICE traversal has been specified for these tunneled

protocols, they should be straightforward to support as overlay link protocols.

6.6.2. Framing Header

In order to support unreliable links and to allow for quick detection of link failures when using reliable end-to-end transports, each message is wrapped in a very simple framing layer (FramedMessage), which is used only for each hop. This layer contains a sequence number which can then be used for ACKs. The same header is used for both reliable and unreliable transports for simplicity of implementation.

The definition of FramedMessage is:

```
enum { data(128), ack(129), (255) } FramedMessageType;

struct {
  FramedMessageType       type;

  select (type) {
    case data:
      uint32              sequence;
      opaque              message<0..2^24-1>;

    case ack:
      uint32              ack_sequence;
      uint32              received;
  };
} FramedMessage;
```

The type field of the PDU is set to indicate whether the message is data or an acknowledgement.

If the message is of type "data", then the remainder of the PDU is as follows:

sequence
: The sequence number. This increments by one for each framed message sent over this transport session.

message
: The message that is being transmitted.

Each connection has it own sequence number space. Initially, the value is zero, and it increments by exactly one for each message sent over that connection.

When the receiver receives a message, it SHOULD immediately send an ACK message. The receiver MUST keep track of the 32 most recent sequence numbers received on this association in order to generate the appropriate ACK.

If the PDU is of type "ack", the contents are as follows:

ack_sequence
: The sequence number of the message being acknowledged.

received
: A bitmask indicating if each of the previous 32 sequence numbers before this packet has been among the 32 packets most recently received on this connection. When a packet is received with a sequence number N, the receiver looks at the sequence number of the 32 previously received packets on this connection. We call the previously received packet number M. For each of the previous 32 packets, if the sequence number M is less than N but greater than N-32, the N-M bit of the received bitmask is set to one; otherwise, it is set to zero. Note that a bit being set to one indicates positively that a particular packet was received, but a bit being set to zero means only that it is unknown whether or not the packet has been received, because it might have been received before the 32 most recently received packets.

The received field bits in the ACK provide a high degree of redundancy so that the sender can figure out which packets the receiver has received and can then estimate packet loss rates. If the sender also keeps track of the time at which recent sequence numbers have been sent, the RTT (round-trip time) can be estimated.

Note that because retransmissions receive new sequence numbers, multiple ACKs may be received for the same message. This approach provides more information than traditional TCP sequence numbers, but care must be taken when applying algorithms designed based on TCP's stream-oriented sequence number.

6.6.3. Simple Reliability

When RELOAD is carried over DTLS or another unreliable link protocol, it needs to be used with a reliability and congestion control mechanism, which is provided on a hop-by-hop basis. The basic principle is that each message, regardless of whether or not it carries a request or response, will get an ACK and be reliably retransmitted. The receiver's job is very simple, and is limited to just sending ACKs. All the complexity is at the sender side. This allows the sending implementation to trade off performance versus implementation complexity without affecting the wire protocol.

Because the receiver's role is limited to providing packet acknowledgements, a wide variety of congestion control algorithms can be implemented on the sender side while using the same basic wire protocol. The sender algorithm used MUST meet the requirements of [RFC5405].

6.6.3.1. Stop and Wait Sender Algorithm

This section describes one possible implementation of a sender algorithm for Simple Reliability. It is adequate for overlays running on underlying networks with low latency and loss (LANs) or low-traffic overlays on the Internet.

A node MUST NOT have more than one unacknowledged message on the DTLS connection at a time. Note that because retransmissions of the same message are given new sequence numbers, there may be multiple unacknowledged sequence numbers in use.

The RTO (Retransmission TimeOut) is based on an estimate of the RTT. The value for RTO is calculated separately for each DTLS session. Implementations can use a static value for RTO or a dynamic estimate, which will result in better performance. For implementations that use a static value, the default value for RTO is 500 ms. Nodes MAY use smaller values of RTO if it is known that all nodes are within the local network. The default RTO MAY be set to a larger value, which is RECOMMENDED if it is known in advance (such as on high-latency access links) that the RTT is larger.

Implementations that use a dynamic estimate to compute the RTO MUST use the algorithm described in RFC 6298 [RFC6298], with the exception that the value of RTO SHOULD NOT be rounded up to the nearest second, but instead rounded up to the nearest millisecond. The RTT of a successful STUN transaction from the ICE stage is used as the initial measurement for formula 2.2 of RFC 6298. The sender keeps track of the time each message was sent for all recently sent messages. Any time an ACK is received, the sender can compute the RTT for that message by looking at the time the ACK was received and the time when the message was sent. This is used as a subsequent RTT measurement for formula 2.3 of RFC 6298 to update the RTO estimate. (Note that because retransmissions receive new sequence numbers, all received ACKs are used.)

An initiating node SHOULD retransmit a message if it has not received an ACK after an interval of RTO (transit nodes do not retransmit at this layer). The node MUST double the time to wait after each retransmission. For each retransmission, the sequence number MUST be incremented.

Retransmissions continue until a response is received, until a total of 5 requests have been sent, until there has been a hard ICMP error [RFC1122], or until a TLS alert indicating the end of the connection has been sent or received. The sender knows a response was received when it receives an ACK with a sequence number that indicates it is a response to one of the transmissions of this message. For example, assuming an RTO of 500 ms, requests would be sent at times 0 ms, 500 ms, 1500 ms, 3500 ms, and 7500 ms. If all retransmissions for a message fail, then the sending node SHOULD close the connection routing the message.

To determine when a link might be failing without waiting for the final timeout, observe when no ACKs have been received for an entire RTO interval, and then wait for three retransmissions to occur beyond that point. If no ACKs have been received by the time the third retransmission occurs, it is RECOMMENDED that the link be removed from the Routing Table. The link MAY be restored to the Routing Table if ACKs resume before the connection is closed, as described above.

A sender MUST wait 10 ms between receipt of an ACK and transmission of the next message.

6.6.4. DTLS/UDP with SR

This overlay link protocol consists of DTLS over UDP while implementing the SR protocol. STUN connectivity checks and keepalives are used. Any compliant sender algorithm may be used.

6.6.5. TLS/TCP with FH, No-ICE

This overlay link protocol consists of TLS over TCP with the framing header. Because ICE is not used, STUN connectivity checks are not used upon establishing the TCP connection, nor are they used for keepalives.

Because the TCP layer's application-level timeout is too slow to be useful for overlay routing, the Overlay Link implementation MUST use the framing header to measure the RTT of the connection and calculate an RTO as specified in Section 2 of [RFC6298]. The resulting RTO is not used for retransmissions, but rather as a timeout to indicate when the link SHOULD be removed from the Routing Table. It is RECOMMENDED that such a connection be retained for 30 seconds to determine if the failure was transient before concluding the link has failed permanently.

When sending candidates for TLS/TCP with FH, No-ICE, a passive candidate MUST be provided.

6.6.6. DTLS/UDP with SR, No-ICE

This overlay link protocol consists of DTLS over UDP while implementing the Simple Reliability protocol. Because ICE is not used, no STUN connectivity checks or keepalives are used.

6.7. Fragmentation and Reassembly

In order to allow transmission over datagram protocols such as DTLS, RELOAD messages may be fragmented.

Any node along the path can fragment the message, but only the final destination reassembles the fragments. When a node takes a packet and fragments it, each fragment has a full copy of the forwarding header, but the data after the forwarding header is broken up into appropriately sized chunks. The size of the payload chunks needs to take into account space to allow the Via and Destination Lists to grow. Each fragment MUST contain a full copy of the Via List, Destination List, and ForwardingOptions and MUST contain at least 256 bytes of the message body. If these elements cannot fit within the MTU of the underlying datagram protocol, RELOAD fragmentation is not performed, and IP-layer fragmentation is allowed to occur. The length field MUST contain the size of the message after fragmentation. When a message MUST be fragmented, it SHOULD be split into equal-sized fragments that are no larger than the Path MTU (PMTU) of the next overlay link minus 32 bytes. This is to allow the Via List to grow before further fragmentation is required.

Note that this fragmentation is not optimal for the end-to-end path -- a message may be refragmented multiple times as it traverses the overlay, but it is assembled only at the final destination. This option has been chosen as it is far easier to implement than end-to-end (e2e) PMTU discovery across an ever-changing overlay and it effectively addresses the reliability issues of relying on IP-layer fragmentation. However, Ping can be used to allow e2e PMTU discovery to be implemented if desired.

Upon receipt of a fragmented message by the intended peer, the peer holds the fragments in a holding buffer until the entire message has been received. The message is then reassembled into a single message and processed. In order to mitigate denial-of-service (DoS) attacks, receivers SHOULD time out incomplete fragments after the maximum request lifetime (15 seconds). This time was derived from looking at the end-to-end retransmission time and saving fragments long enough for the full end-to-end retransmissions to take place. Ideally, the receiver would have enough buffer space to deal with as many fragments as can arrive in the maximum request lifetime. However, if

the receiver runs out of buffer space to reassemble a message, it MUST drop the message.

The fragment field of the forwarding header is used to encode fragmentation information. The offset is the number of bytes between the end of the forwarding header and the start of the data. The first fragment therefore has an offset of 0. The last fragment indicator MUST be appropriately set. If the message is not fragmented, it is simply treated as if it is the only fragment: the last fragment bit is set and the offset is 0, resulting in a fragment value of 0xC0000000.

Note: The reason for this definition of the fragment field is that originally, the high bit was defined in part of the specification as "is fragmented", so there was some specification ambiguity about how to encode messages with only one fragment. This ambiguity was resolved in favor of always encoding as the "last" fragment with offset 0, thus simplifying the receiver code path, but resulting in the high bit being redundant. Because messages MUST be set with the high bit set to 1, implementations SHOULD discard any message with it set to 0. Implementations (presumably legacy ones) which choose to accept such messages MUST either ignore the remaining bits or ensure that they are 0. They MUST NOT try to interpret as fragmented messages with the high bit set low.

7. Data Storage Protocol

RELOAD provides a set of generic mechanisms for storing and retrieving data in the Overlay Instance. These mechanisms can be used for new applications simply by defining new code points and a small set of rules. No new protocol mechanisms are required.

The basic unit of stored data is a single StoredData structure:

```
struct {
  uint32                length;
  uint64                storage_time;
  uint32                lifetime;
  StoredDataValue       value;
  Signature             signature;
} StoredData;
```

The contents of this structure are as follows:

length
: The size of the StoredData structure, in bytes, excluding the size of length itself.

storage_time
The time when the data was stored, represented as the number of milliseconds elapsed since midnight Jan 1, 1970 UTC, not counting leap seconds. This will have the same values for seconds as standard UNIX or POSIX time. More information can be found at [UnixTime]. Any attempt to store a data value with a storage time before that of a value already stored at this location MUST generate an Error_Data_Too_Old error. This prevents rollback attacks. The node SHOULD make a best-effort attempt to use a correct clock to determine this number. However, the protocol does not require synchronized clocks: the receiving peer uses the storage time in the previous store, not its own clock. Clock values are used so that when clocks are generally synchronized, data may be stored in a single transaction, rather than querying for the value of a counter before the actual store.

If a node attempting to store new data in response to a user request (rather than as an overlay maintenance operation such as occurs when healing the overlay from a partition) is rejected with an Error_Data_Too_Old error, the node MAY elect to perform its store using a storage_time that increments the value used with the previous store (this may be obtained by doing a Fetch). This situation may occur when the clocks of nodes storing to this location are not properly synchronized.

lifetime
The validity period for the data, in seconds, starting from the time the peer receives the StoreReq.

value
The data value itself, as described in Section 7.2.

signature
A signature, as defined in Section 7.1.

Each Resource-ID specifies a single location in the Overlay Instance. However, each location may contain multiple StoredData values, distinguished by Kind-ID. The definition of a Kind describes both the data values which may be stored and the data model of the data. Some data models allow multiple values to be stored under the same Kind-ID. Section 7.2 describes the available data models. Thus, for instance, a given Resource-ID might contain a single-value element stored under Kind-ID X and an array containing multiple values stored under Kind-ID Y.

7.1. Data Signature Computation

Each StoredData element is individually signed. However, the signature also must be self-contained and must cover the Kind-ID and Resource-ID, even though they are not present in the StoredData structure. The input to the signature algorithm is:

```
resource_id || kind || storage_time || StoredDataValue ||
SignerIdentity
```

where || indicates concatenation and where these values are:

resource_id
: The Resource-ID where this data is stored.

kind
: The Kind-ID for this data.

storage_time
: The contents of the storage_time data value.

StoredDataValue
: The contents of the stored data value, as described in the previous sections.

SignerIdentity
: The signer identity, as defined in Section 6.3.4.

Once the signature has been computed, the signature is represented using a signature element, as described in Section 6.3.4.

Note that there is no necessary relationship between the validity window of a certificate and the expiry of the data it is authenticating. When signatures are verified, the current time MUST be compared to the certificate validity period. Stored data MAY be set to expire after the signing certificate's validity period. Such signatures are not considered valid after the signing certificate expires. Implementations may "garbage collect" such data at their convenience, either by purging it automatically (perhaps by setting the upper bound on data storage to the lifetime of the signing certificate) or by simply leaving it in place until it expires naturally and relying on users of that data to notice the expired signing certificate.

7.2. Data Models

The protocol currently defines the following data models:

- single value
- array
- dictionary

These are represented with the StoredDataValue structure. The actual data model is known from the Kind being stored.

```
struct {
  Boolean                exists;
  opaque                 value<0..2^32-1>;
} DataValue;

struct {
  select (DataModel) {
    case single_value:
      DataValue            single_value_entry;

    case array:
      ArrayEntry           array_entry;

    case dictionary:
      DictionaryEntry      dictionary_entry;

    /* This structure may be extended */
  };
} StoredDataValue;
```

The following sections discuss the properties of each data model.

7.2.1. Single Value

A single-value element is a simple sequence of bytes. There may be only one single-value element for each Resource-ID, Kind-ID pair.

A single value element is represented as a DataValue, which contains the following two elements:

exists
: This value indicates whether the value exists at all. If it is set to False, it means that no value is present. If it is True, this means that a value is present. This gives the protocol a mechanism for indicating nonexistence as opposed to emptiness.

value
The stored data.

7.2.2. Array

An array is a set of opaque values addressed by an integer index. Arrays are zero based. Note that arrays can be sparse. For instance, a Store of "X" at index 2 in an empty array produces an array with the values [NA, NA, "X"]. Future attempts to fetch elements at index 0 or 1 will return values with "exists" set to False.

An array element is represented as an ArrayEntry:

```
struct {
  uint32                  index;
  DataValue               value;
} ArrayEntry;
```

The contents of this structure are:

index
The index of the data element in the array.

value
The stored data.

7.2.3. Dictionary

A dictionary is a set of opaque values indexed by an opaque key, with one value for each key. A single dictionary entry is represented as a DictionaryEntry:

```
typedef opaque           DictionaryKey<0..2^16-1>;

struct {
  DictionaryKey          key;
  DataValue              value;
} DictionaryEntry;
```

The contents of this structure are:

key
The dictionary key for this value.

value
The stored data.

7.3. Access Control Policies

Every Kind which is storable in an overlay MUST be associated with an access control policy. This policy defines whether a request from a given node to operate on a given value should succeed or fail. It is anticipated that only a small number of generic access control policies are required. To that end, this section describes a small set of such policies, and Section 14.4 establishes a registry for new policies, if required. Each policy has a short string identifier which is used to reference it in the Configuration Document.

In the following policies, the term "signer" refers to the signer of the StoredValue object and, in the case of non-replica stores, to the signer of the StoreReq message. That is, in a non-replica store, both the signer of the StoredValue and the signer of the StoreReq MUST conform to the policy. In the case of a replica store, the signer of the StoredValue MUST conform to the policy, and the StoreReq itself MUST be checked as described in Section 7.4.1.1.

7.3.1. USER-MATCH

In the USER-MATCH policy, a given value MUST be written (or overwritten) if and only if the signer's certificate has a user name which hashes (using the hash function for the overlay) to the Resource-ID for the resource. Recall that the certificate may, depending on the overlay configuration, be self-signed.

7.3.2. NODE-MATCH

In the NODE-MATCH policy, a given value MUST be written (or overwritten) if and only if the signer's certificate has a specified Node-ID which hashes (using the hash function for the overlay) to the Resource-ID for the resource and that Node-ID is the one indicated in the SignerIdentity value cert_hash.

7.3.3. USER-NODE-MATCH

The USER-NODE-MATCH policy may be used only with dictionary types. In the USER-NODE-MATCH policy, a given value MUST be written (or overwritten) if and only if the signer's certificate has a user name which hashes (using the hash function for the overlay) to the Resource-ID for the resource. In addition, the dictionary key MUST be equal to the Node-ID in the certificate, and that Node-ID MUST be the one indicated in the SignerIdentity value cert_hash.

7.3.4. NODE-MULTIPLE

In the NODE-MULTIPLE policy, a given value MUST be written (or overwritten) if and only if the signer's certificate contains a Node-ID such that H(Node-ID || i) is equal to the Resource-ID for some small integer value of i and that Node-ID is the one indicated in the SignerIdentity value cert_hash. When this policy is in use, the maximum value of i MUST be specified in the Kind definition.

Note that because i is not carried on the wire, the verifier MUST iterate through potential i values, up to the maximum value, to determine whether a store is acceptable.

7.4. Data Storage Methods

RELOAD provides several methods for storing and retrieving data:

- Store values in the overlay.
- Fetch values from the overlay.
- Stat: Get metadata about values in the overlay.
- Find the values stored at an individual peer.

These methods are described in the following sections.

7.4.1. Store

The Store method is used to store data in the overlay. The format of the Store request depends on the data model, which is determined by the Kind.

7.4.1.1. Request Definition

A StoreReq message is a sequence of StoreKindData values, each of which represents a sequence of stored values for a given Kind. The same Kind-ID MUST NOT be used twice in a given store request. Each value is then processed in turn. These operations MUST be atomic. If any operation fails, the state MUST be rolled back to what it was before the request was received.

The store request is defined by the StoreReq structure:

```
    struct {
        KindId                  kind;
        uint64                  generation_counter;
        StoredData              values<0..2^32-1>;
    } StoreKindData;

    struct {
        ResourceId              resource;
        uint8                   replica_number;
        StoreKindData           kind_data<0..2^32-1>;
    } StoreReq;
```

A single Store request stores data of a number of Kinds to a single resource location. The contents of the structure are:

resource
: The resource at which to store.

replica_number
: The number of this replica. When a storing peer saves replicas to other peers, each peer is assigned a replica number, starting from 1, that is sent in the Store message. This field is set to 0 when a node is storing its own data. This allows peers to distinguish replica writes from original writes. Different topologies may choose to allocate or interpret the replica number differently (see Section 10.4).

kind_data
: A series of elements, one for each Kind of data to be stored.

The peer MUST check that it is responsible for the resource if the replica number is zero; if it is not, the peer must reject the request. The peer MUST check that it expects to be a replica for the resource and that the request sender is consistent with being the responsible node (i.e., that the receiving peer does not know of a better node) if the replica number is nonzero; if the request sender is not consistent, it should reject the request.

Each StoreKindData element represents the data to be stored for a single Kind-ID. The contents of the element are:

kind
: The Kind-ID. Implementations MUST reject requests corresponding to unknown Kinds.

generation_counter
The expected current state of the generation counter (approximately the number of times that this object has been written; see below for details).

values
The value or values to be stored. This may contain one or more stored_data values, depending on the data model associated with each Kind.

The peer MUST perform the following checks:

- The Kind-ID is known and supported.
- The signatures over each individual data element, if any, are valid. If this check fails, the request MUST be rejected with an Error_Forbidden error.
- Each element is signed by a credential which is authorized to write this Kind at this Resource-ID. If this check fails, the request MUST be rejected with an Error_Forbidden error.
- For original (non-replica) stores, the StoreReq is signed by a credential which is authorized to write this Kind at this Resource-ID. If this check fails, the request MUST be rejected with an Error_Forbidden error.
- For replica stores, the StoreReq is signed by a Node-ID which is a plausible node to either have originally stored the value or have been in the replica set. What this means is overlay specific, but in the case of the Chord-based DHT defined in this specification, replica StoreReqs MUST come from nodes which are either in the known replica set for a given resource or which are closer than some node in the replica set. If this check fails, the request MUST be rejected with an Error_Forbidden error.
- For original (non-replica) stores, the peer MUST check that if the generation counter is nonzero, it equals the current value of the generation counter for this Kind. This feature allows the generation counter to be used in a way similar to the HTTP ETag feature.
- For replica Stores, the peer MUST set the generation counter to match the generation counter in the message and MUST NOT check the generation counter against the current value. Replica Stores MUST NOT use a generation counter of 0.

- The storage time values are greater than that of any values which would be replaced by this Store.
- The size and number of the stored values are consistent with the limits specified in the overlay configuration.
- If the data is signed with identity_type set to "none" and/or SignatureAndHashAlgorithm values set to {0, 0} ("anonymous" and "none"), the StoreReq MUST be rejected with an Error_forbidden error. Only synthesized data returned by the storage can use these values (see Section 7.4.2.2)

If all these checks succeed, the peer MUST attempt to store the data values. For non-replica stores, if the store succeeds and the data is changed, then the peer MUST increase the generation counter by at least 1. If there are multiple stored values in a single StoreKindData, it is permissible for the peer to increase the generation counter by only 1 for the entire Kind-ID or by 1 or more than 1 for each value. Accordingly, all stored data values MUST have a generation counter of 1 or greater. 0 is used in the Store request to indicate that the generation counter should be ignored for processing this request. However, the responsible peer should increase the stored generation counter and should return the correct generation counter in the response.

When a peer stores data previously stored by another node (e.g., for replicas or topology shifts), it MUST adjust the lifetime value downward to reflect the amount of time the value was stored at the peer. The adjustment SHOULD be implemented by an algorithm equivalent to the following: at the time the peer initially receives the StoreReq, it notes the local time T. When it then attempts to do a StoreReq to another node, it should decrement the lifetime value by the difference between the current local time and T.

Unless otherwise specified by the usage, if a peer attempts to store data previously stored by another node (e.g., for replicas or topology shifts) and that store fails with either an Error_Generation_Counter_Too_Low or an Error_Data_Too_Old error, the peer MUST fetch the newer data from the peer generating the error and use that to replace its own copy. This rule allows resynchronization after partitions heal.

When a network partition is being healed and unless otherwise specified, the default merging rule is to act as if all the values that need to be merged were stored and as if the order they were stored in corresponds to the stored time values associated with (and carried in) their values. Because the stored time values are those associated with the peer which did the writing, clock skew is

generally not an issue. If two nodes are on different partitions, write to the same location, and have clock skew, this can create merge conflicts. However, because RELOAD deliberately segregates storage so that data from different users and peers is stored in different locations, and a single peer will typically only be in a single network partition, this case will generally not arise.

The properties of stores for each data model are as follows:

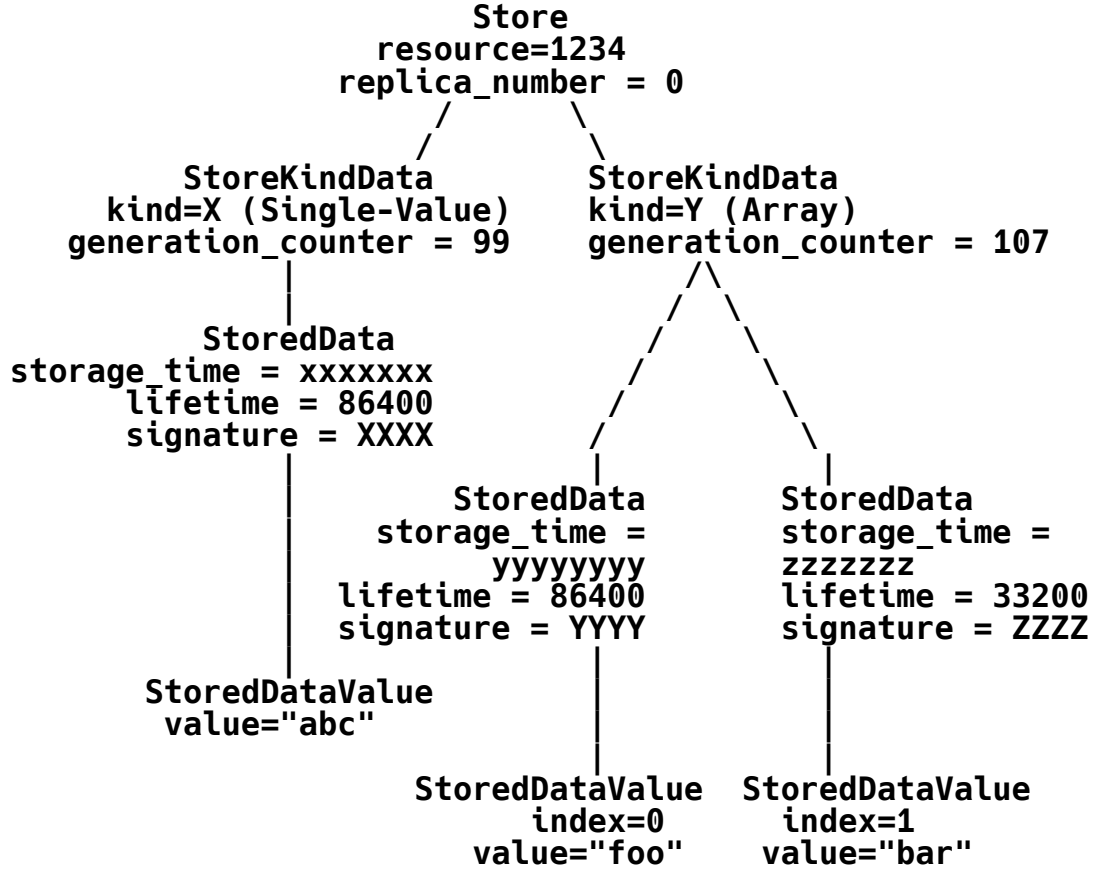
single-value: A store of a new single-value element creates the element if it does not exist and overwrites any existing value with the new value.

array: A store of an array entry replaces (or inserts) the given value at the location specified by the index. Because arrays are sparse, a store past the end of the array extends it with nonexistent values (exists = False) as required. A store at index 0xffffffff places the new value at the end of the array, regardless of the length of the array. The resulting StoredData has the correct index value when it is subsequently fetched.

dictionary: A store of a dictionary entry replaces (or inserts) the given value at the location specified by the dictionary key.

The following figure shows the relationship between these structures for an example store which stores the following values at resource "1234":

- The value "abc" is in the single-value location for Kind X.
- The value "foo" at index 0 is in the array for Kind Y.
- The value "bar" at index 1 is in the array for Kind Y.



7.4.1.2. Response Definition

In response to a successful Store request, the peer MUST return a StoreAns message containing a series of StoreKindResponse elements, which contains the current value of the generation counter for each Kind-ID, as well as a list of the peers where the data will be replicated by the node processing the request.

```
struct {
  KindId                  kind;
  uint64                  generation_counter;
  NodeId                  replicas<0..2^16-1>;
} StoreKindResponse;

struct {
  StoreKindResponse       kind_responses<0..2^16-1>;
} StoreAns;
```

The contents of each StoreKindResponse are:

kind
: The Kind-ID being represented.

generation_counter
: The current value of the generation counter for that Kind-ID.

replicas
: The list of other peers at which the data was/will be replicated. In overlays and applications where the responsible peer is intended to store redundant copies, this allows the storing node to independently verify that the replicas have in fact been stored. It does this verification by using the Stat method (see Section 7.4.3). Note that the storing node is not required to perform this verification.

The response itself is just StoreKindResponse values packed end to end.

If any of the generation counters in the request precede the corresponding stored generation counter, then the peer MUST fail the entire request and respond with an Error_Generation_Counter_Too_Low error. The error_info in the ErrorResponse MUST be a StoreAns response containing the correct generation counter for each Kind and the replica list, which will be empty. For original (non-replica) stores, a node which receives such an error SHOULD attempt to fetch the data and, if the storage_time value is newer, replace its own data with that newer data. This rule improves data consistency in the case of partitions and merges.

If the data being stored is too large for the allowed limit by the given usage, then the peer MUST fail the request and generate an Error_Data_Too_Large error.

If any type of request tries to access a data Kind that the peer does not know about, the peer MUST fail the request and generate an Error_Unknown_Kind error. The error_info in the Error_Response is:

```
KindId unknown_kinds<0..2^8-1>;
```

which lists all the Kinds that were unrecognized. A node which receives this error MUST generate a ConfigUpdate message which contains the appropriate Kind definition (assuming which, in fact, a Kind which was defined in the configuration document was used).

7.4.1.3. Removing Values

RELOAD does not have an explicit Remove operation. Rather, values are Removed by storing "nonexistent" values in their place. Each DataValue contains a boolean value called "exists" which indicates whether a value is present at that location. In order to effectively remove a value, the owner stores a new DataValue with "exists" set to False:

```
exists = False

value = {} (0 length)
```

The owner SHOULD use a lifetime for the nonexistent value that is at least as long as the remainder of the lifetime of the value it is replacing. Otherwise, it is possible for the original value to be accidentally or maliciously re-stored after the storing node has expired it. Note that a window of vulnerability for replay attack still exists after the original lifetime has expired (as with any store). This attack can be mitigated by doing a nonexistent store with a very long lifetime.

Storing nodes MUST treat these nonexistent values the same way they treat any other stored value, including overwriting the existing value, replicating them, and aging them out as necessary when the lifetime expires. When a stored nonexistent value's lifetime expires, it is simply removed from the storing node, as happens when any other stored value expires.

Note that in the case of arrays and dictionaries, expiration may create an implicit, unsigned "nonexistent" value to represent a gap in the data structure, as might happen when any value is aged out.

However, this value isn't persistent, nor is it replicated. It is simply synthesized by the storing node.

7.4.2. Fetch

The Fetch request retrieves one or more data elements stored at a given Resource-ID. A single Fetch request can retrieve multiple different Kinds.

7.4.2.1. Request Definition

Fetch requests are defined by the FetchReq structure:

```
struct {
  int32            first;
  int32            last;
} ArrayRange;

struct {
  KindId                  kind;
  uint64                  generation;
  uint16                  length;

  select (DataModel) {
    case single_value: ;    /* Empty */

    case array:
         ArrayRange       indices<0..2^16-1>;

    case dictionary:
         DictionaryKey    keys<0..2^16-1>;

    /* This structure may be extended */

  } model_specifier;
} StoredDataSpecifier;

struct {
  ResourceId              resource;
  StoredDataSpecifier     specifiers<0..2^16-1>;
} FetchReq;
```

The contents of the Fetch requests are as follows:

resource
: The Resource-ID to fetch from.

specifiers
: A sequence of StoredDataSpecifier values, each specifying some of the data values to retrieve.

Each StoredDataSpecifier specifies a single Kind of data to retrieve and, if appropriate, the subset of values that are to be retrieved. The contents of the StoredDataSpecifier structure are as follows:

kind
: The Kind-ID of the data being fetched. Implementations SHOULD reject requests corresponding to unknown Kinds unless specifically configured otherwise.

DataModel
: The data model of the data. This is not transmitted on the wire, but comes from the definition of the Kind.

generation
: The last generation counter that the requesting node saw. This may be used to avoid unnecessary fetches, or it may be set to zero.

length
: The length of the rest of the structure, thus allowing extensibility.

model_specifier
: A reference to the data value being requested within the data model specified for the Kind. For instance, if the data model is "array", it might specify some subset of the values.

The model_specifier is as follows:

- If the data model is single value, the specifier is empty.
- If the data model is array, the specifier contains a list of ArrayRange elements, each of which contains two integers. The first integer is the beginning of the range, and the second is the end of the range. 0 is used to indicate the first element, and 0xffffffff is used to indicate the final element. The first integer MUST be less than or equal to the second. While multiple ranges MAY be specified, they MUST NOT overlap.
- If the data model is dictionary, then the specifier contains a list of the dictionary keys being requested. If no keys are specified, then this is a wildcard fetch and all key-value pairs are returned.

The generation counter is used to indicate the requester's expected state of the storing peer. If the generation counter in the request matches the stored counter, then the storing peer returns a response with no StoredData values.

7.4.2.2. Response Definition

The response to a successful Fetch request is a FetchAns message containing the data requested by the requester.

```
struct {
  KindId                kind;
  uint64                generation;
  StoredData            values<0..2^32-1>;
} FetchKindResponse;

struct {
  FetchKindResponse     kind_responses<0..2^32-1>;
} FetchAns;
```

The FetchAns structure contains a series of FetchKindResponse structures. There MUST be one FetchKindResponse element for each Kind-ID in the request.

The contents of the FetchKindResponse structure are as follows:

kind
: The Kind that this structure is for.

generation
: The generation counter for this Kind.

values
: The relevant values. If the generation counter in the request matches the generation counter in the stored data, then no StoredData values are returned. Otherwise, all relevant data values MUST be returned. A nonexistent value (i.e., one which the node has no knowledge of) is represented by a synthetic value with "exists" set to False and has an empty signature. Specifically, the identity_type is set to "none", the SignatureAndHashAlgorithm values are set to {0, 0} ("anonymous" and "none", respectively), and the signature value is of zero length. This removes the need for the responding node to do signatures for values which do not exist. These signatures are unnecessary, as the entire response is signed by that node. Note that entries which have been removed by the procedure given in Section 7.4.1.3 and which have not yet expired also have exists = False, but have valid signatures from the node which did the store.

Upon receipt of a FetchAns message, nodes MUST verify the signatures on all the received values. Any values with invalid signatures (including expired certificates) MUST be discarded. Note that this implies that implementations which wish to store data for long periods of time must have certificates with appropriate expiration dates or must re-store periodically. Implementations MAY return the subset of values with valid signatures, but in that case, they SHOULD somehow signal to the application that a partial response was received.

There is one subtle point about signature computation on arrays. If the storing node uses the append feature (where the index=0xffffffff), then the index in the StoredData that is returned will not match that used by the storing node, which would break the signature. In order to avoid this issue, the index value in the array is set to zero before the signature is computed. This implies that malicious storing nodes can reorder array entries without being detected.

7.4.3. Stat

The Stat request is used to get metadata (length, generation counter, digest, etc.) for a stored element without retrieving the element itself. The name is from the UNIX stat(2) system call, which performs a similar function for files in a file system. It also allows the requesting node to get a list of matching elements without requesting the entire element.

7.4.3.1. Request Definition

The Stat request is identical to the Fetch request. It simply specifies the elements to get metadata about.

```
struct {
  ResourceId              resource;
  StoredDataSpecifier     specifiers<0..2^16-1>;
} StatReq;
```

7.4.3.2. Response Definition

The Stat response contains the same sort of entries that a Fetch response would contain. However, instead of containing the element data, it contains metadata.

```
struct {
  Boolean                exists;
  uint32                 value_length;
  HashAlgorithm          hash_algorithm;
  opaque                 hash_value<0..255>;
} MetaData;

struct {
  uint32                 index;
  MetaData               value;
} ArrayEntryMeta;

struct {
  DictionaryKey          key;
  MetaData               value;
} DictionaryEntryMeta;

struct {
  select (DataModel) {
    case single_value:
      MetaData              single_value_entry;

    case array:
      ArrayEntryMeta        array_entry;

    case dictionary:
      DictionaryEntryMeta   dictionary_entry;

    /* This structure may be extended */
  };
} MetaDataValue;

struct {
  uint32                  value_length;
  uint64                  storage_time;
  uint32                  lifetime;
  MetaDataValue           metadata;
} StoredMetaData;
```

```
struct {
  KindId                kind;
  uint64                generation;
  StoredMetaData        values<0..2^32-1>;
} StatKindResponse;

struct {
  StatKindResponse      kind_responses<0..2^32-1>;
} StatAns;
```

The structures used in StatAns parallel those used in FetchAns: a response consists of multiple StatKindResponse values, one for each Kind that was in the request. The contents of the StatKindResponse are the same as those in the FetchKindResponse, except that the values list contains StoredMetaData entries instead of StoredData entries.

The contents of the StoredMetaData structure are the same as the corresponding fields in StoredData, except that there is no signature field and the value is a MetaDataValue rather than a StoredDataValue.

A MetaDataValue is a variant structure, like a StoredDataValue, except for the types of each arm, which replace DataValue with MetaData.

The only new structure is MetaData, which has the following contents:

exists
: Same as in DataValue.

value_length
: The length of the stored value.

hash_algorithm
: The hash algorithm used to perform the digest of the value.

hash_value
: A digest using hash_algorithm on the value field of the DataValue, including its 4 leading length bytes.

7.4.4. Find

The Find request can be used to explore the Overlay Instance. A Find request for a Resource-ID R and a Kind-ID T retrieves the Resource-ID, if any, of the resource of Kind T known to the target peer which is closest to R. This method can be used to walk the Overlay Instance by iteratively fetching R_n+1=nearest(1 + R_n).

7.4.4.1. Request Definition

The FindReq message contains a Resource-ID and a series of Kind-IDs identifying the resource the peer is interested in.

```
struct {
  ResourceId                resource;
  KindId                    kinds<0..2^8-1>;
} FindReq;
```

The request contains a list of Kind-IDs which the Find is for, as indicated below:

resource
: The desired Resource-ID.

kinds
: The desired Kind-IDs. Each value MUST appear only once. Otherwise, the request MUST be rejected with an error.

7.4.4.2. Response Definition

A response to a successful Find request is a FindAns message containing the closest Resource-ID on the peer for each Kind specified in the request.

```
struct {
  KindId                    kind;
  ResourceId                closest;
} FindKindData;

struct {
  FindKindData              results<0..2^16-1>;
} FindAns;
```

If the processing peer is not responsible for the specified Resource-ID, it SHOULD return an Error_Not_Found error code.

For each Kind-ID in the request, the response MUST contain a FindKindData indicating the closest Resource-ID for that Kind-ID, unless the Kind is not allowed to be used with Find, in which case a FindKindData for that Kind-ID MUST NOT be included in the response. If a Kind-ID is not known, then the corresponding Resource-ID MUST be 0. Note that different Kind-IDs may have different closest Resource-IDs.

The response is simply a series of FindKindData elements, one per Kind, concatenated end to end. The contents of each element are:

kind
: The Kind-ID.

closest
: The closest Resource-ID to the specified Resource-ID. It is 0 if no Resource-ID is known.

Note that the response does not contain the contents of the data stored at these Resource-IDs. If the requester wants this, it must retrieve it using Fetch.

7.4.5. Defining New Kinds

There are two ways to define a new Kind. The first is by writing a document and registering the Kind-ID with IANA. This is the preferred method for Kinds which may be widely used and reused. The second method is to simply define the Kind and its parameters in the Configuration Document using the section of Kind-ID space set aside for private use. This method MAY be used to define ad hoc Kinds in new overlays.

However a Kind is defined, the definition MUST include:

- The meaning of the data to be stored (in some textual form).
- The Kind-ID.
- The data model (single value, array, dictionary, etc.).
- The access control model.

In addition, when Kinds are registered with IANA, each Kind is assigned a short string name which is used to refer to it in Configuration Documents.

While each Kind needs to define what data model is used for its data, this does not mean that it must define new data models. Where practical, Kinds should use the existing data models. The intention is that the basic data model set be sufficient for most applications/usages.

8. Certificate Store Usage

The Certificate Store Usage allows a node to store its certificate in the overlay.

A user/node MUST store its certificate at Resource-IDs derived from two Resource Names:

- The user name in the certificate.
- The Node-ID in the certificate.

Note that in the second case, the certificate for a peer is not stored at its Node-ID but rather at a hash of its Node-ID. The intention here (as is common throughout RELOAD) is to avoid making a peer responsible for its own data.

New certificates are stored at the end of the list. This structure allows users to store an old and a new certificate that both have the same Node-ID, which allows for migration of certificates when they are renewed.

This usage defines the following Kinds:

Name: CERTIFICATE_BY_NODE

Data Model: The data model for CERTIFICATE_BY_NODE data is array.

Access Control: NODE-MATCH

Name: CERTIFICATE_BY_USER

Data Model: The data model for CERTIFICATE_BY_USER data is array.

Access Control: USER-MATCH

9. TURN Server Usage

The TURN Server Usage allows a RELOAD peer to advertise that it is prepared to be a TURN server, as defined in [RFC5766]. When a node starts up, it joins the overlay network and forms several connections in the process. If the ICE stage in any of these connections returns a reflexive address that is not the same as the peer's perceived address, then the peer is behind a NAT and SHOULD NOT be a candidate for a TURN server. Additionally, if the peer's IP address is in the private address space range as defined by [RFC1918], then it is also

SHOULD NOT be a candidate for a TURN server. Otherwise, the peer SHOULD assume that it is a potential TURN server and follow the procedures below.

If the node is a candidate for a TURN server, it will insert some pointers in the overlay so that other peers can find it. The overlay configuration file specifies a turn-density parameter that indicates how many times each TURN server SHOULD record itself in the overlay. Typically, this should be set to the reciprocal of the estimate of what percentage of peers will act as TURN servers. If the turn-density is not set to zero, for each value, called d, between 1 and turn-density, the peer forms a Resource Name by concatenating its Node-ID and the value d. This Resource Name is hashed to form a Resource-ID. The address of the peer is stored at that Resource-ID using type TURN-SERVICE and the TurnServer object:

```
struct {
  uint8                   iteration;
  IpAddressPort           server_address;
} TurnServer;
```

The contents of this structure are as follows:

iteration
: The d value.

server_address
: The address at which the TURN server can be contacted.

Note: Correct functioning of this algorithm depends on having turn-density be a reasonable estimate of the reciprocal of the proportion of nodes in the overlay that can act as TURN servers. If the turn-density value in the configuration file is too low, the process of finding TURN servers becomes more expensive, as multiple candidate Resource-IDs must be probed to find a TURN server.

Peers that provide this service need to support the TURN extensions to STUN for media relay, as defined in [RFC5766].

This usage defines the following Kind to indicate that a peer is willing to act as a TURN server:

Name: TURN-SERVICE

Data Model: The TURN-SERVICE Kind stores a single value for each Resource-ID.

Access Control: NODE-MULTIPLE, with a maximum iteration of counter 20.

Peers MAY find other servers by selecting a random Resource-ID and then doing a Find request for the appropriate Kind-ID with that Resource-ID. The Find request gets routed to a random peer based on the Resource-ID. If that peer knows of any servers, they will be returned. The returned response may be empty if the peer does not know of any servers, in which case the process gets repeated with some other random Resource-ID. As long as the ratio of servers relative to peers is not too low, this approach will result in finding a server relatively quickly.

Note to implementers: The certificates used by TurnServer entries need to be retained, as described in Section 6.3.4.

10. Chord Algorithm

This algorithm is assigned the name CHORD-RELOAD to indicate that it is an adaptation of the basic Chord-based DHT algorithm.

This algorithm differs from the Chord algorithm that was originally presented in [Chord]. It has been updated based on more recent research results and implementation experiences, and to adapt it to the RELOAD protocol. Here is a short list of differences:

- The original Chord algorithm specified that a single predecessor and a successor list be stored. The CHORD-RELOAD algorithm attempts to have more than one predecessor and successor. The predecessor sets help other neighbors learn their successor list.

- The original Chord specification and analysis called for iterative routing. RELOAD specifies recursive routing. In addition to the performance implications, the cost of NAT traversal dictates recursive routing.

- Finger Table entries are indexed in the opposite order. Original Chord specifies finger[0] as the immediate successor of the peer. CHORD-RELOAD specifies finger[0] as the peer 180 degrees around the ring from the peer. This change was made to simplify discussion and implementation of variable-sized Finger Tables. However, with either approach, no more than O(log N) entries should typically be stored in a Finger Table.

- The stabilize() and fix_fingers() algorithms in the original Chord algorithm are merged into a single periodic process. Stabilization is implemented slightly differently because of the larger neighborhood, and fix_fingers is not as aggressive to

reduce load, nor does it search for optimal matches of the Finger Table entries.

- RELOAD allows for a 128-bit hash instead of a 160-bit hash, as RELOAD is not designed to be used in networks with close to or more than 2^128 nodes or objects (and it is hard to see how one would assemble such a network).

- RELOAD uses randomized finger entries, as described in Section 10.7.4.2.

- The CHORD-RELOAD algorithm allows the use of either reactive or periodic recovery. The original Chord paper used periodic recovery. Reactive recovery provides better performance in small overlays, but is believed to be unstable in large overlays (greater than 1000) with high levels of churn [handling-churn-usenix04]. The overlay configuration file specifies a "chord-reactive" element that indicates whether reactive recovery should be used.

10.1. Overview

The algorithm described here, CHORD-RELOAD, is a modified version of the Chord algorithm. In Chord (and in the algorithm described here), nodes are arranged in a ring, with node n being adjacent to nodes n-1 and n+1 and with all arithmetic being done modulo 2^{k}, where k is the length of the Node-ID in bits, so that node 2^{k} - 1 is directly before node 0.

Each peer keeps track of a Finger Table and a Neighbor Table. The Neighbor Table contains at least the three peers before and after this peer in the DHT ring. There may not be three entries in all cases, such as small rings or while the ring topology is changing. The first entry in the Finger Table contains the peer halfway around the ring from this peer, the second entry contains the peer that is 1/4th of the way around, the third entry contains the peer that is 1/8th of the way around, and so on. Fundamentally, the Chord DHT can be thought of as a doubly linked list formed by knowing the successors and predecessor peers in the Neighbor Table, sorted by the Node-ID. As long as the successor peers are correct, the DHT will return the correct result. The pointers to the prior peers are kept to enable the insertion of new peers into the list structure. Keeping multiple predecessor and successor pointers makes it possible to maintain the integrity of the data structure even when consecutive peers simultaneously fail. The Finger Table forms a skip list [wikiSkiplist] so that entries in the linked list can be found in O(log(N)) time instead of the typical O(N) time that a linked list would provide, where N represents the number of nodes in the DHT.

The Neighbor Table and Finger Table entries contain logical Node-IDs as values, but the actual mapping of an IP level addressing information to reach that Node-ID is kept in the Connection Table.

A peer, x, is responsible for a particular Resource-ID, k, if k is less than or equal to x and k is greater than p, where p is the Node-ID of the previous peer in the Neighbor Table. Care must be taken when computing to note that all math is modulo 2^128.

10.2. Hash Function

For this Chord-based Topology Plug-in, the size of the Resource-ID is 128 bits. The hash of a Resource-ID MUST be computed using SHA-1 [RFC3174], and then the SHA-1 result MUST be truncated to the most significant 128 bits.

10.3. Routing

The Routing Table is conceptually the union of the Neighbor Table and the Finger Table.

If a peer is not responsible for a Resource-ID k, but is directly connected to a node with Node-ID k, then it MUST route the message to that node. Otherwise, it MUST route the request to the peer in the Routing Table that has the largest Node-ID that is in the interval between the peer and k. If no such node is found, the peer finds the smallest Node-ID that is greater than k and MUST route the message to that node.

10.4. Redundancy

When a peer receives a Store request for Resource-ID k and it is responsible for Resource-ID k, it MUST store the data and return a success response. It MUST then send a Store request to its successor in the Neighbor Table and to that peer's successor, incrementing the replica number for each successor. Note that these Store requests are addressed to those specific peers, even though the Resource-ID they are being asked to store is outside the range that they are responsible for. The peers receiving these SHOULD check that they came from an appropriate predecessor in their Neighbor Table and that they are in a range that this predecessor is responsible for. Then, they MUST store the data. They do not themselves perform further Stores, because they can determine that they are not responsible for the Resource-ID.

Note that this Topology Plug-in does not use the replica number for purposes other than knowing the difference between a replica and a non-replica.

Managing replicas as the overlay changes is described in Section 10.7.3.

The sequential replicas used in this overlay algorithm protect against peer failure but not against malicious peers. Additional replication from the Usage is required to protect resources from such attacks, as discussed in Section 13.5.4.

10.5. Joining

The join process for a Joining Node (JN) with Node-ID n is as follows:

1. JN MUST connect to its chosen bootstrap node, as specified in Section 11.4.

2. JN SHOULD send an Attach request to the Admitting Peer (AP) for Resource-ID n+1. The "send_update" flag can be used to acquire the Routing Table of AP.

3. JN SHOULD send Attach requests to initiate connections to each of the peers in the Neighbor Table as well as to the desired peers in the Finger Table. Note that this does not populate their Routing Tables, but only their Connection Tables, so JN will not get messages that it is expected to route to other nodes.

4. JN MUST enter into its Routing Table all the peers that it has successfully contacted.

5. JN MUST send a Join to AP. The AP MUST send the response to the Join.

6. AP MUST do a series of Store requests to JN to store the data that JN will be responsible for.

7. AP MUST send JN an Update explicitly labeling JN as its predecessor. At this point, JN is part of the ring and is responsible for a section of the overlay. AP MAY now forget any data which is assigned to JN and not AP. AP SHOULD NOT forget any data where AP is the replica set for the data.

8. The AP MUST send an Update to all of its neighbors (including JN) with the new values of its neighbor set (including JN).

9. JN MUST send Updates to all of the peers in its Neighbor Table.

If JN sends an Attach to AP with send_update, it immediately knows most of its expected neighbors from AP's Routing Table update and MAY directly connect to them. This is the RECOMMENDED procedure.

If for some reason JN does not get AP's Routing Table, it MAY still populate its Neighbor Table incrementally. It SHOULD send a Ping directed at Resource-ID n+1 (directly after its own Resource-ID). This allows JN to discover its own successor. Call that node p0. JN then SHOULD send a Ping to p0+1 to discover its successor (p1). This process MAY be repeated to discover as many successors as desired. The values for the two peers before p will be found at a later stage, when n receives an Update. An alternate procedure is to send Attaches to those nodes rather than Pings, which form the connections immediately, but may be slower if the nodes need to collect ICE candidates.

In order to set up its i'th Finger Table entry, JN MUST send an Attach to peer n+2^(128-i). This will be routed to a peer in approximately the right location around the ring. (Note that the first entry in the Finger Table has i=1 and not i=0 in this formulation.)

The Joining Node MUST NOT send any Update message placing itself in the overlay until it has successfully completed an Attach with each peer that should be in its Neighbor Table.

10.6. Routing Attaches

When a peer needs to Attach to a new peer in its Neighbor Table, it MUST source-route the Attach request through the peer from which it learned the new peer's Node-ID. Source-routing these requests allows the overlay to recover from instability.

All other Attach requests, such as those for new Finger Table entries, are routed conventionally through the overlay.

10.7. Updates

An Update for this DHT is defined as:

```
     enum { invalidChordUpdateType(0),
            peer_ready(1), neighbors(2), full(3), (255) }
          ChordUpdateType;

     struct {
        uint32                  uptime;
        ChordUpdateType         type;
        select (type){
         case peer_ready:                    /* Empty */
           ;

         case neighbors:
           NodeId               predecessors<0..2^16-1>;
           NodeId               successors<0..2^16-1>;

         case full:
           NodeId               predecessors<0..2^16-1>;
           NodeId               successors<0..2^16-1>;
           NodeId               fingers<0..2^16-1>;
       };
     } ChordUpdate;
```

The "uptime" field contains the time this peer has been up in seconds.

The "type" field contains the type of the update, which depends on the reason the update was sent.

peer_ready
: This peer is ready to receive messages. This message is used to indicate that a node which has Attached is a peer and can be routed through. It is also used as a connectivity check to non-neighbor peers.

neighbors
: This version is sent to members of the Chord Neighbor Table.

full
: This version is sent to peers which request an Update with a RouteQueryReq.

If the message is of type "neighbors", then the contents of the message will be:

predecessors
The predecessor set of the Updating peer.

successors
The successor set of the Updating peer.

If the message is of type "full", then the contents of the message will be:

predecessors
The predecessor set of the Updating peer.

successors
The successor set of the Updating peer.

fingers
The Finger Table of the Updating peer, in numerically ascending order.

A peer MUST maintain an association (via Attach) to every member of its neighbor set. A peer MUST attempt to maintain at least three predecessors and three successors, even though this will not be possible if the ring is very small. It is RECOMMENDED that O(log(N)) predecessors and successors be maintained in the neighbor set. There are many ways to estimate N, some of which are discussed in [DHT-RELOAD].

10.7.1. Handling Neighbor Failures

Every time a connection to a peer in the Neighbor Table is lost (as determined by connectivity pings or the failure of some request), the peer MUST remove the entry from its Neighbor Table and replace it with the best match it has from the other peers in its Routing Table. If using reactive recovery, the peer MUST send an immediate Update to all nodes in its Neighbor Table. The update will contain all the Node-IDs of the current entries of the table (after the failed one has been removed). Note that when replacing a successor, the peer SHOULD delay the creation of new replicas for the successor replacement hold-down time (30 seconds) after removing the failed entry from its Neighbor Table in order to allow a triggered update to inform it of a better match for its Neighbor Table.

If the neighbor failure affects the peer's range of responsible IDs, then the Update MUST be sent to all nodes in its Connection Table.

A peer MAY attempt to reestablish connectivity with a lost neighbor either by waiting additional time to see if connectivity returns or by actively routing a new Attach to the lost peer. Details for these procedures are beyond the scope of this document. In the case of an attempt to reestablish connectivity with a lost neighbor, the peer MUST be removed from the Neighbor Table. Such a peer is returned to the Neighbor Table once connectivity is reestablished.

If connectivity is lost to all successor peers in the Neighbor Table, then this peer SHOULD behave as if it is joining the network and MUST use Pings to find a peer and send it a Join. If connectivity is lost to all the peers in the Finger Table, this peer SHOULD assume that it has been disconnected from the rest of the network, and it SHOULD periodically try to join the DHT.

10.7.2. Handling Finger Table Entry Failure

If a Finger Table entry is found to have failed (as determined by connectivity pings or the failure of some request), all references to the failed peer MUST be removed from the Finger Table and replaced with the closest preceding peer from the Finger Table or Neighbor Table.

If using reactive recovery, the peer MUST initiate a search for a new Finger Table entry, as described below.

10.7.3. Receiving Updates

When a peer x receives an Update request, it examines the Node-IDs in the UpdateReq and at its Neighbor Table and decides if this UpdateReq would change its Neighbor Table. This is done by taking the set of peers currently in the Neighbor Table and comparing them to the peers in the Update request. There are two major cases:

- The UpdateReq contains peers that match x's Neighbor Table, so no change is needed to the neighbor set.
- The UpdateReq contains peers that x does not know about that should be in x's Neighbor Table; i.e., they are closer than entries in the Neighbor Table.

In the first case, no change is needed.

In the second case, x MUST attempt to Attach to the new peers, and if it is successful, it MUST adjust its neighbor set accordingly. Note that x can maintain the now inferior peers as neighbors, but it MUST remember the closer ones.

After any Pings and Attaches are done, if the Neighbor Table changes and the peer is using reactive recovery, the peer MUST send an Update request to each member of its Connection Table. These Update requests are what end up filling in the predecessor/successor tables of peers that this peer is a neighbor to. A peer MUST NOT enter itself in its successor or predecessor table and instead should leave the entries empty.

If peer x is responsible for a Resource-ID R and x discovers that the replica set for R (the next two nodes in its successor set) has changed, it MUST send a Store for any data associated with R to any new node in the replica set. It SHOULD NOT delete data from peers which have left the replica set.

When peer x detects that it is no longer in the replica set for a resource R (i.e., there are three predecessors between x and R), it SHOULD delete all data associated with R from its local store.

When a peer discovers that its range of responsible IDs has changed, it MUST send an Update to all entries in its Connection Table.

10.7.4. Stabilization

There are four components to stabilization:

1. Exchange Updates with all peers in its Neighbor Table to exchange state.

2. Search for better peers to place in its Finger Table.

3. Search to determine if the current Finger Table size is sufficiently large.

4. Search to determine if the overlay has partitioned and needs to recover.

10.7.4.1. Updating the Neighbor Table

A peer MUST periodically send an Update request to every peer in its Neighbor Table. The purpose of this is to keep the predecessor and successor lists up to date and to detect failed peers. The default time is about every ten minutes, but the configuration server SHOULD set this in the Configuration Document using the "chord-update-interval" element (denominated in seconds). A peer SHOULD randomly offset these Update requests so they do not occur all at once.

10.7.4.2. Refreshing the Finger Table

A peer MUST periodically search for new peers to replace invalid entries in the Finger Table. For peer x, the i'th Finger Table entry is valid if it is in the range [x+2^(128-i), x+2^(128-(i-1))-1]. Invalid entries occur in the Finger Table when a previous Finger Table entry has failed or when no peer has been found in that range.

Two possible methods for searching for new peers for the Finger Table entries are presented:

Alternative 1: A peer selects one entry in the Finger Table from among the invalid entries. It pings for a new peer for that Finger Table entry. The selection SHOULD be exponentially weighted to attempt to replace earlier (lower i) entries in the Finger Table. A simple way to implement this selection is to search through the Finger Table entries from i=1, and each time an invalid entry is encountered, send a Ping to replace that entry with probability 0.5.

Alternative 2: A peer monitors the Update messages received from its connections to observe when an Update indicates a peer that would be used to replace an invalid Finger Table entry, i, and flags that entry in the Finger Table. Every "chord-ping-interval" seconds, the peer selects from among those flagged candidates using an exponentially weighted probability, as above.

When searching for a better entry, the peer SHOULD send the Ping to a Node-ID selected randomly from that range. Random selection is preferred over a search for strictly spaced entries to minimize the effect of churn on overlay routing [minimizing-churn-sigcomm06]. An implementation or subsequent specification MAY choose a method for selecting Finger Table entries other than choosing randomly within the range. Any such alternate methods SHOULD be employed only on Finger Table stabilization and not for the selection of initial Finger Table entries unless the alternative method is faster and imposes less overhead on the overlay.

A peer SHOULD NOT send Ping requests looking for new finger table entries more often than the configuration element "chord-ping-interval", which defaults to 3600 seconds (one per hour).

A peer MAY choose to keep connections to multiple peers that can act for a given Finger Table entry.

10.7.4.3. Adjusting Finger Table Size

If the Finger Table has fewer than 16 entries, the node SHOULD attempt to discover more fingers to grow the size of the table to 16. The value 16 was chosen to ensure high odds of a node maintaining connectivity to the overlay even with strange network partitions.

For many overlays, 16 Finger Table entries will be enough, but as an overlay grows very large, more than 16 entries may be required in the Finger Table for efficient routing. An implementation SHOULD be capable of increasing the number of entries in the Finger Table to 128 entries.

Although log(N) entries are all that are required for optimal performance, careful implementation of stabilization will result in no additional traffic being generated when maintaining a Finger Table larger than log(N) entries. Implementers are encouraged to make use of RouteQuery and algorithms for determining where new Finger Table entries may be found. Complete details of possible implementations are outside the scope of this specification.

A simple approach to sizing the Finger Table is to ensure that the Finger Table is large enough to contain at least the final successor in the peer's Neighbor Table.

10.7.4.4. Detecting Partitioning

To detect that a partitioning has occurred and to heal the overlay, a peer P MUST periodically repeat the discovery process used in the initial join for the overlay to locate an appropriate bootstrap node, B. P SHOULD then send a Ping for its own Node-ID routed through B. If a response is received from peer S', which is not P's successor, then the overlay is partitioned and P SHOULD send an Attach to S' routed through B, followed by an Update sent to S'. (Note that S' may not be in P's Neighbor Table once the overlay is healed, but the connection will allow S' to discover appropriate neighbor entries for itself via its own stabilization.)

Future specifications may describe alternative mechanisms for determining when to repeat the discovery process.

10.8. Route Query f.in 3

For CHORD-RELOAD, the RouteQueryReq contains no additional information. The RouteQueryAns contains the single Node-ID of the next peer to which the responding peer would have routed the request message in recursive routing:

```
struct {
   NodeId                  next_peer;
} ChordRouteQueryAns;
```

The contents of this structure are as follows:

next_peer
: The peer to which the responding peer would route the message in order to deliver it to the destination listed in the request.

If the requester has set the send_update flag, the responder SHOULD initiate an Update immediately after sending the RouteQueryAns.

10.9. Leaving

To support extensions, such as [DHT-RELOAD], peers SHOULD send a Leave request to all members of their Neighbor Table before exiting the Overlay Instance. The overlay_specific_data field MUST contain the ChordLeaveData structure, defined below:

```
            enum { invalidChordLeaveType(0),
                   from_succ(1), from_pred(2), (255) }
                 ChordLeaveType;

             struct {
               ChordLeaveType         type;

                select (type) {
                  case from_succ:
                    NodeId             successors<0..2^16-1>;

                  case from_pred:
                    NodeId            predecessors<0..2^16-1>;
                };
             } ChordLeaveData;
```

The "type" field indicates whether the Leave request was sent by a predecessor or a successor of the recipient:

from_succ
: The Leave request was sent by a successor.

from_pred
: The Leave request was sent by a predecessor.

If the type of the request is "from_succ", the contents will be:

successors
: The sender's successor list.

If the type of the request is "from_pred", the contents will be:

predecessors
: The sender's predecessor list.

Any peer which receives a Leave for a peer n in its neighbor set MUST follow procedures as if it had detected a peer failure as described in Section 10.7.1.

11. Enrollment and Bootstrap

The section defines the format of the configuration data as well the process to join a new overlay.

11.1. Overlay Configuration

This specification defines a new content type "application/p2p-overlay+xml" for a MIME entity that contains overlay information. An example document is shown below:

```
<?xml version="1.0" encoding="UTF-8"?>
<overlay xmlns="urn:ietf:params:xml:ns:p2p:config-base"
   xmlns:ext="urn:ietf:params:xml:ns:p2p:config-ext1"
   xmlns:chord="urn:ietf:params:xml:ns:p2p:config-chord">
   <configuration instance-name="overlay.example.org" sequence="22"
       expiration="2002-10-10T07:00:00Z" ext:ext-example="stuff" >
       <topology-plugin> CHORD-RELOAD </topology-plugin>
       <node-id-length>16</node-id-length>
       <root-cert>
MIIDJDCCAo2gAwIBAgIBADANBgkqhkiG9w0BAQUFADBwMQswCQYDVQQGEwJVUzET
MBEGA1UECBMKQ2FsaWZvcm5pYTERMA8GA1UEBxMIU2FuIEpvc2UxDjAMBgNVBAoT
BXNpcGl0MSkwJwYDVQQLEyBTaXBpdCBUZXN0IENlcnRpZmljYXRlIEF1dGhvcml0
eTAeFw0wMzA3MTgxMjIxNTJaFw0xMzA3MTUxMjIxNTJaMHAxCzAJBgNVBAYTAlVT
MRMwEQYDVQQIEwpDYWxpZm9ybmlhMREwDwYDVQQHEwhTYW4gSm9zZTEOMAwGA1UE
```

```
   ChMFc2lwaXQxKTAnBgNVBAsTIFNpcGl0IFRlc3QgQ2VydGlmaWNhdGUgQXV0aG9y
   aXR5MIGfMA0GCSqGSIb3DQEBAQUAA4GNADCBiQKBgQDDIh6DkcUDLDyK9BEUxkud
   +nJ4xrCVGKfgjHm6XaSuHiEtnfELHM+9WymzkBNzZpJu30yzsxwfKoIKugdNUrD4
   N3viCicwcN35LgP/KnbN34cavXHr4ZlqxH+OdKB3hQTpQa38A7YXdaoz6goW2ft5
   Mi74z03GNKP/G9BoKOGd5QIDAQABo4HNMIHKMB0GA1UdDgQWBBRrRhcU6pR2JYBU
   bhNU2qHjVBShtjCBmgYDVR0jBIGSMIGPgBRrRhcU6pR2JYBUbhNU2qHjVBShtqF0
   pHIwcDELMAkGA1UEBhMCVVMxEzARBgNVBAgTCkNhbGlmb3JuaWExETAPBgNVBAcT
   CFNhbiBKb3NlMQ4wDAYDVQQKEwVzaXBpdDEpMCcGA1UECxMgU2lwaXQgVGVzdCBD
   ZXJ0aWZpY2F0ZSBBdXRob3JpdHmCAQAwDAYDVR0TBAUwAwEB/zANBgkqhkiG9w0B
   AQUFAAOBgQCWbRvv1ZGTRXxbH8/EqkdSCzSoUPrs+rQqR0xdQac9wNY/nlZbkR3O
   qAezG6Sfmklvf+DOg5RxQq/+Y6I03LRepc7KeVDpaplMFGnpfKsibETMipwzayNQ
   QgUf4cKBiF+65Ue7hZuDJa2EMv8qW4twEhGDYclpFU9YozyS1OhvUg==
          </root-cert>
          <root-cert> YmFkIGNlcnQK </root-cert>
          <enrollment-server>https://example.org</enrollment-server>
          <enrollment-server>https://example.net</enrollment-server>
          <self-signed-permitted
                    digest="sha1">false</self-signed-permitted>
          <bootstrap-node address="192.0.0.1" port="6084" />
          <bootstrap-node address="192.0.2.2" port="6084" />
          <bootstrap-node address="2001:DB8::1" port="6084" />
          <turn-density> 20 </turn-density>
          <clients-permitted> false </clients-permitted>
          <no-ice> false </no-ice>
          <chord:chord-update-interval>
              400</chord:chord-update-interval>
          <chord:chord-ping-interval>30</chord:chord-ping-interval>
          <chord:chord-reactive> true </chord:chord-reactive>
          <shared-secret> password </shared-secret>
          <max-message-size>4000</max-message-size>
          <initial-ttl> 30 </initial-ttl>
          <overlay-reliability-timer> 3000 </overlay-reliability-timer>
          <overlay-link-protocol>TLS</overlay-link-protocol>
          <configuration-signer>47112162e84c69ba</configuration-signer>
          <kind-signer> 47112162e84c69ba </kind-signer>
          <kind-signer> 6eba45d31a900c06 </kind-signer>
          <bad-node> 6ebc45d31a900c06 </bad-node>
          <bad-node> 6ebc45d31a900ca6 </bad-node>

          <ext:example-extension> foo </ext:example-extension>

          <mandatory-extension>
              urn:ietf:params:xml:ns:p2p:config-ext1
          </mandatory-extension>

          <required-kinds>
            <kind-block>
              <kind name="SIP-REGISTRATION">
```

```
                <data-model>SINGLE</data-model>
                <access-control>USER-MATCH</access-control>
                <max-count>1</max-count>
                <max-size>100</max-size>
              </kind>
              <kind-signature>
                   VGhpcyBpcyBub3QgcmlnaHQhCg==
              </kind-signature>
            </kind-block>
            <kind-block>
              <kind id="2000">
                <data-model>ARRAY</data-model>
                <access-control>NODE-MULTIPLE</access-control>
                <max-node-multiple>3</max-node-multiple>
                <max-count>22</max-count>
                <max-size>4</max-size>
                <ext:example-kind-extension> 1
                          </ext:example-kind-extension>
              </kind>
              <kind-signature>
                 VGhpcyBpcyBub3QgcmlnaHQhCg==
              </kind-signature>
            </kind-block>
          </required-kinds>
      </configuration>
      <signature> VGhpcyBpcyBub3QgcmlnaHQhCg== </signature>

      <configuration instance-name="other.example.net">
      </configuration>
      <signature> VGhpcyBpcyBub3QgcmlnaHQhCg== </signature>

    </overlay>
```

The file MUST be a well-formed XML document, and it SHOULD contain an encoding declaration in the XML declaration. The file MUST use the UTF-8 character encoding. The namespaces for the elements defined in this specification are urn:ietf:params:xml:ns:p2p:config-base and urn:ietf:params:xml:ns:p2p:config-chord.

Note that elements or attributes that are defined as type xsd:boolean in the RELAX NG schema (Section 11.1.1) have two lexical representations, "1" or "true" for the concept true, and "0" or "false" for the concept false. Whitespace and case processing follows the rules of [OASIS.relax_ng] and XML Schema Datatypes [W3C.REC-xmlschema-2-20041028].

The file MAY contain multiple "configuration" elements, where each one contains the configuration information for a different overlay. Each configuration element MAY be followed by signature elements that provide a signature over the preceding configuration element. Each configuration element has the following attributes:

instance-name
: The name of the overlay (referred to as "overlay name" in this specification)

expiration
: Time in the future at which this overlay configuration is no longer valid. The node SHOULD retrieve a new copy of the configuration at a randomly selected time that is before the expiration time. Note that if the certificates expire before a new configuration is retried, the node will not be able to validate the configuration file. All times MUST conform to the Internet date/time format defined in [RFC3339] and be specified using UTC.

sequence
: A monotonically increasing sequence number between 0 and 2^16-2.

Inside each overlay element, the following elements can occur:

topology-plug-in
: This element defines the overlay algorithm being used. If missing, the default is "CHORD-RELOAD".

node-id-length
: This element contains the length of a NodeId (NodeIdLength), in bytes. This value MUST be between 16 (128 bits) and 20 (160 bits). If this element is not present, the default of 16 is used.

root-cert
: This element contains a base-64-encoded X.509v3 certificate that is a root trust anchor used to sign all certificates in this overlay. There can be more than one root-cert element.

enrollment-server
: This element contains the URL at which the enrollment server can be reached in a "url" element. This URL MUST be of type "https:". More than one enrollment-server element MAY be present. Note that there is no necessary relationship between the overlay name/ configuration server name and the enrollment server name.

self-signed-permitted
: This element indicates whether self-signed certificates are permitted. If it is set to "true", then self-signed certificates are allowed, in which case the enrollment-server and root-cert elements MAY be absent. Otherwise, it SHOULD be absent, but MAY be set to "false". This element also contains an attribute "digest", which indicates the digest to be used to compute the Node-ID. Valid values for this parameter are "sha1" and "sha256", representing SHA-1 [RFC3174] and SHA-256 [RFC6234], respectively. Implementations MUST support both of these algorithms.

bootstrap-node
: This element represents the address of one of the bootstrap nodes. It has an attribute called "address" that represents the IP address (either IPv4 or IPv6, since they can be distinguished) and an optional attribute called "port" that represents the port and defaults to 6084. The IPv6 address is in typical hexadecimal form using standard period and colon separators as specified in [RFC5952]. More than one bootstrap-node element MAY be present.

turn-density
: This element is a positive integer that represents the approximate reciprocal of density of nodes that can act as TURN servers. For example, if 5% of the nodes can act as TURN servers, this element would be set to 20. If it is not present, the default value is 1. If there are no TURN servers in the overlay, it is set to zero.

clients-permitted
: This element represents whether clients are permitted or whether all nodes must be peers. If clients are permitted, the element MUST be set to "true" or be absent. If the nodes are not allowed to remain clients after the initial join, the element MUST be set to "false". There is currently no way for the overlay to enforce this.

no-ice
: This element represents whether nodes are REQUIRED to use the "No-ICE" Overlay Link protocols in this overlay. If it is absent, it is treated as if it were set to "false".

chord-update-interval
: The update frequency for the CHORD-RELOAD Topology Plug-in (see Section 10).

chord-ping-interval
: The Ping frequency for the CHORD-RELOAD Topology Plug-in (see Section 10).

chord-reactive
: Whether reactive recovery SHOULD be used for this overlay. It is set to "true" or "false". If missing, the default is "true" (see Section 10).

shared-secret
: If shared secret mode is used, this element contains the shared secret. The security guarantee here is that any agent which is able to access the Configuration Document (presumably protected by some sort of HTTP access control or network topology) is able to recover the shared secret and hence join the overlay.

max-message-size
: Maximum size, in bytes, of any message in the overlay. If this value is not present, the default is 5000.

initial-ttl
: Initial default TTL for messages (see Section 6.3.2). If this value is not present, the default is 100.

overlay-reliability-timer
: Default value for the end-to-end retransmission timer for messages, in milliseconds. If not present, the default value is 3000. The value MUST be at least 200 milliseconds, which means the minimum time delay before dropping a link is 1000 milliseconds.

overlay-link-protocol
: Indicates a permissible overlay link protocol (see Section 6.6.1 for requirements for such protocols). An arbitrary number of these elements may appear. If none appear, then this implies the default value, "TLS", which refers to the use of TLS and DTLS. If one or more elements appear, then no default value applies.

kind-signer
: This contains a single Node-ID in hexadecimal and indicates that the certificate with this Node-ID is allowed to sign Kinds. Identifying kind-signer by Node-ID instead of certificate allows the use of short-lived certificates without constantly having to provide an updated configuration file.

configuration-signer
: This contains a single Node-ID in hexadecimal and indicates that the certificate with this Node-ID is allowed to sign configurations for this instance-name. Identifying the signer by Node-ID instead of certificate allows the use of short-lived certificates without constantly having to provide an updated configuration file.

bad-node
: This contains a single Node-ID in hexadecimal and indicates that the certificate with this Node-ID MUST NOT be considered valid. This allows certificate revocation. An arbitrary number of these elements can be provided. Note that because certificates may expire, bad-node entries need be present only for the lifetime of the certificate. Technically speaking, bad Node-IDs may be reused after their certificates have expired. The requirement for Node-IDs to be pseudorandomly generated gives this event a vanishing probability.

mandatory-extension
: This element contains the name of an XML namespace that a node joining the overlay MUST support. The presence of a mandatory-extension element does not require the extension to be used in the current configuration file, but can indicate that it may be used in the future. Note that the namespace is case-sensitive, as specified in Section 2.3 of [w3c-xml-namespaces]. More than one mandatory-extension element MAY be present.

Inside each configuration element, the required-kinds element MAY also occur. This element indicates the Kinds that members MUST support and contains multiple kind-block elements that each define a single Kind that MUST be supported by nodes in the overlay. Each kind-block consists of a single kind element and a kind-signature. The kind element defines the Kind. The kind-signature is the signature computed over the kind element.

Each kind element has either an id attribute or a name attribute. The name attribute is a string representing the Kind (the name registered to IANA), while the id is an integer Kind-ID allocated out of private space.

In addition, the kind element MUST contain the following elements:

max-count
: The maximum number of values which members of the overlay must support.

data-model
: The data model to be used.

max-size
: The maximum size of individual values.

access-control
: The access control model to be used.

The kind element MAY also contain the following element:

max-node-multiple
: If the access control is NODE-MULTIPLE, this element MUST be included. This indicates the maximum value for the i counter. It MUST be an integer greater than 0.

All of the non-optional values MUST be provided. If the Kind is registered with IANA, the data-model and access-control elements MUST match those in the Kind registration, and clients MUST ignore them in favor of the IANA versions. Multiple kind-block elements MAY be present.

The kind-block element also MUST contain a "kind-signature" element. This signature is computed across the kind element from the beginning of the first < of the kind element to the end of the last > of the kind element in the same way as the signature element described later in this section. kind-block elements MUST be signed by a node listed in the kind-signers block of the current configuration. Receivers MUST verify the signature prior to accepting a kind-block.

The configuration element MUST be treated as a binary blob that cannot be changed -- including any whitespace changes -- or the signature will break. The signature MUST be computed by taking each configuration element and starting from, and including, the first < at the start of <configuration> up to and including the > in </configuration> and treating this as a binary blob that MUST be signed using the standard SecurityBlock defined in Section 6.3.4. The SecurityBlock MUST be base-64 encoded using the base64 alphabet from [RFC4648] and MUST be put in the signature element following the configuration object in the configuration file. Any configuration file MUST be signed by one of the configuration-signer elements from the previous extant configuration. Recipients MUST verify the signature prior to accepting the configuration file.

When a node receives a new configuration file, it MUST change its configuration to meet the new requirements. This may require the node to exit the DHT and rejoin. If a node is not capable of supporting the new requirements, it MUST exit the overlay. If some information about a particular Kind changes from what the node previously knew about the Kind (for example, the max size), the new information in the configuration files overrides any previously learned information. If any Kind data was signed by a node that is no longer allowed to sign Kinds, that Kind MUST be discarded along with any stored information of that Kind. Note that forcing an avalanche restart of the overlay with a configuration change that requires rejoining the overlay may result in serious performance problems, including total collapse of the network if configuration

parameters are not properly considered. Such an event may be necessary in case of a compromised CA or similar problem, but for large overlays, it should be avoided in almost all circumstances.

11.1.1. RELAX NG Grammar

The grammar for the configuration data is:

```
namespace chord = "urn:ietf:params:xml:ns:p2p:config-chord"
namespace local = ""
default namespace p2pcf = "urn:ietf:params:xml:ns:p2p:config-base"
namespace rng = "http://relaxng.org/ns/structure/1.0"

anything =
    (element * { anything }
     | attribute * { text }
     | text)*

foreign-elements = element * - (p2pcf:* | local:* | chord:*)
                   { anything }*
foreign-attributes = attribute * - (p2pcf:*|local:*|chord:*)
                     { text }*
foreign-nodes = (foreign-attributes | foreign-elements)*

start =  element p2pcf:overlay {
      overlay-element
}

overlay-element &=  element configuration {
            attribute instance-name { xsd:string },
            attribute expiration { xsd:dateTime }?,
            attribute sequence { xsd:long }?,
            foreign-attributes*,
            parameter
        }+
overlay-element &= element signature {
            attribute algorithm { signature-algorithm-type }?,
            xsd:base64Binary
        }*

signature-algorithm-type |= "rsa-sha1"
signature-algorithm-type |=  xsd:string # signature alg extensions

parameter &= element topology-plugin { topology-plugin-type }?
topology-plugin-type |= xsd:string # topo plugin extensions
parameter &= element max-message-size { xsd:unsignedInt }?
parameter &= element initial-ttl { xsd:int }?
parameter &= element root-cert { xsd:base64Binary }*
```

```
   parameter &= element required-kinds { kind-block* }?
   parameter &= element enrollment-server { xsd:anyURI }*
   parameter &= element kind-signer {  xsd:string }*
   parameter &= element configuration-signer {  xsd:string }*
   parameter &= element bad-node {  xsd:string }*
   parameter &= element no-ice { xsd:boolean }?
   parameter &= element shared-secret { xsd:string }?
   parameter &= element overlay-link-protocol { xsd:string }*
   parameter &= element clients-permitted { xsd:boolean }?
   parameter &= element turn-density { xsd:unsignedByte }?
   parameter &= element node-id-length { xsd:int }?
   parameter &= element mandatory-extension { xsd:string }*
   parameter &= foreign-elements*

   parameter &=
       element self-signed-permitted {
           attribute digest { self-signed-digest-type },
           xsd:boolean
       }?
   self-signed-digest-type |= "sha1"
   self-signed-digest-type |=  xsd:string # signature digest extensions

   parameter &= element bootstrap-node {
                   attribute address { xsd:string },
                   attribute port { xsd:int }?
                }*

   kind-block = element kind-block {
       element kind {
           (  attribute name { kind-names }
              | attribute id { xsd:unsignedInt } ),
           kind-parameter
       } &
       element kind-signature  {
           attribute algorithm { signature-algorithm-type }?,
           xsd:base64Binary
       }?
   }

   kind-parameter &= element max-count { xsd:int }
   kind-parameter &= element max-size { xsd:int }
   kind-parameter &= element max-node-multiple { xsd:int }?

   kind-parameter &= element data-model { data-model-type }
   data-model-type |= "SINGLE"
   data-model-type |= "ARRAY"
   data-model-type |= "DICTIONARY"
   data-model-type |=  xsd:string # data model extensions
```

```
kind-parameter &= element access-control { access-control-type }
access-control-type |= "USER-MATCH"
access-control-type |= "NODE-MATCH"
access-control-type |= "USER-NODE-MATCH"
access-control-type |= "NODE-MULTIPLE"
access-control-type |= xsd:string # access control extensions

kind-parameter &= foreign-elements*

kind-names |= "TURN-SERVICE"
kind-names |= "CERTIFICATE_BY_NODE"
kind-names |= "CERTIFICATE_BY_USER"
kind-names |= xsd:string # kind extensions

# Chord specific parameters
topology-plugin-type |= "CHORD-RELOAD"
parameter &= element chord:chord-ping-interval { xsd:int }?
parameter &= element chord:chord-update-interval { xsd:int }?
parameter &= element chord:chord-reactive { xsd:boolean }?
```

11.2. Discovery through Configuration Server

When a node first enrolls in a new overlay, it starts with a discovery process to find a configuration server.

The node MAY start by determining the overlay name. This value MUST be provided by the user or some other out-of-band provisioning mechanism. The out-of-band mechanism MAY also provide an optional URL for the configuration server. If a URL for the configuration server is not provided, the node MUST do a DNS SRV query using a Service name of "reload-config" and a protocol of TCP to find a configuration server and form the URL by appending a path of "/.well-known/reload-config" to the overlay name. This uses the "well-known URI" framework defined in [RFC5785]. For example, if the overlay name was example.com, the URL would be "https://example.com/.well-known/reload-config".

Once an address and URL for the configuration server are determined, the peer MUST form an HTTPS connection to that IP address. If an optional URL for the configuration server was provided, the certificate MUST match the domain name from the URL as described in [RFC2818]; otherwise, the certificate MUST match the overlay name as described in [RFC2818]. If the HTTPS certificates pass the name matching, the node MUST fetch a new copy of the configuration file. To do this, the peer performs a GET to the URL. The result of the HTTP GET is an XML configuration file described above. If the XML is not valid or the instance-name attribute of the overlay-element in the XML does not match the overlay name, this configurations file

SHOULD be discarded. Otherwise, the new configuration MUST replace any previously learned configuration file for this overlay.

For overlays that do not use a configuration server, nodes MUST obtain the configuration information needed to join the overlay through some out-of-band approach, such as an XML configuration file sent over email.

11.3. Credentials

If the Configuration Document contains an enrollment-server element, credentials are REQUIRED to join the Overlay Instance. A peer which does not yet have credentials MUST contact the enrollment server to acquire them.

RELOAD defines its own trivial certificate request protocol. We would have liked to have used an existing protocol, but were concerned about the implementation burden of even the simplest of those protocols, such as [RFC5272] and [RFC5273]. The objective was to have a protocol which could be easily implemented in a Web server which the operator did not control (e.g., in a hosted service) and which was compatible with the existing certificate-handling tooling as used with the Web certificate infrastructure. This means accepting bare PKCS#10 requests and returning a single bare X.509 certificate. Although the MIME types for these objects are defined, none of the existing protocols support exactly this model.

The certificate request protocol MUST be performed over HTTPS. The server certificate MUST match the overlay name as described in [RFC2818]. The request MUST be an HTTP POST with the parameters encoded as described in [RFC2388] and with the following properties:

- If authentication is required, there MUST be form parameters of "password" and "username" containing the user's account name and password in the clear (hence the need for HTTPS). The username and password strings MUST be UTF-8 strings compared as binary objects. Applications using RELOAD SHOULD define any needed string preparation as per [RFC4013] or its successor documents.

- If more than one Node-ID is required, there MUST be a form parameter of "nodeids" containing the number of Node-IDs required.

- There MUST be a form parameter of "csr" with a content type of "application/pkcs10", as defined in [RFC2311], that contains the certificate signing request (CSR).

- The Accept header MUST contain the type "application/pkix-cert", indicating the type that is expected in the response.

The enrollment server MUST authenticate the request using the provided account name and password. The reason for using the RFC 2388 "multipart/form-data" encoding is so that the password parameter will not be encoded in the URL, to reduce the chance of accidental leakage of the password. If the authentication succeeds and the requested user name in the CSR is acceptable, the server MUST generate and return a certificate for the CSR in the "csr" parameter of the request. The SubjectAltName field in the certificate MUST contain the following values:

- One or more Node-IDs which MUST be cryptographically random [RFC4086]. Each MUST be chosen by the enrollment server in such a way that it is unpredictable to the requesting user. For example, the user MUST NOT be informed of potential (random) Node-IDs prior to authenticating. Each is placed in the subjectAltName using the uniformResourceIdentifier type, each MUST contain RELOAD URI, as described in Section 14.15, and each MUST contain a Destination List with a single entry of type "node_id". The enrollment server SHOULD maintain a mapping of users to Node-IDs and if the same user returns (e.g., to have their certificate re-issued), the enrollment server should return the same Node-IDs, thus avoiding the need for implementations to re-store all their data when their certificates expire.

- A single name (the "user name") that this user is allowed to use in the overlay, using type rfc822Name. Enrollment servers SHOULD take care to allow only legal characters in the name (e.g., no embedded NULs), rather than simply accepting any name provided by

  the user. In some usages, the right side of the user name will match the overlay name, but there is no requirement for this match in this specification. Applications using this specification MAY define such a requirement or MAY otherwise limit the allowed range of allowed user names.

The SubjectAltName field in the certificate MUST NOT contain any identities other than those listed above. The subject distinguished name in the certificate MUST be empty.

The certificate MUST be returned as type "application/pkix-cert", as defined in [RFC2585], with an HTTP status code of 200 OK.

Certificate processing errors SHOULD result in an HTTP return code of 403 Forbidden, along with a body of type "text/plain" and body that consists of one of the tokens defined in the following list:

failed_authentication
: The account name and password combination used in the HTTPS request was not valid.

username_not_available
: The requested user name in the CSR was not acceptable.

Node-IDs_not_available
: The number of Node-IDs requested was not acceptable.

bad_CSR
: There was some other problem with the CSR.

If the client receives an unknown token in the body, it SHOULD treat it as a failure for an unknown reason.

The client MUST check that the returned certificate chains back to one of the certificates received in the "root-cert" list of the overlay configuration data (including PKIX BasicConstraints checks). The node then reads the certificate to find the Node-ID it can use.

11.3.1. Self-Generated Credentials

If the "self-signed-permitted" element is present in the configuration and is set to "true", then a node MUST generate its own self-signed certificate to join the overlay. The self-signed certificate MAY contain any user name of the user's choice.

For self-signed certificates containing only one Node-ID, the Node-ID MUST be computed by applying the digest specified in the self-signed-permitted element to the DER representation of the user's public key (more specifically, the subjectPublicKeyInfo) and taking the high-order bits. For self-signed certificates containing multiple Node-IDs, the index of the Node-ID (from 1 to the number of Node-IDs needed) must be prepended as a 4-byte big-endian integer to the DER representation of the user's public key and taking the high-order bits. When accepting a self-signed certificate, nodes MUST check that the Node-ID and public keys match. This prevents Node-ID theft.

Once the node has constructed a self-signed certificate, it MAY join the overlay. It MUST store its certificate in the overlay (Section 8), but SHOULD look to see if the user name is already taken and, if so, choose another user name. Note that this provides protection only against accidental name collisions. Name theft is

still possible. If protection against name theft is desired, then the enrollment service MUST be used.

11.4. Contacting a Bootstrap Node

In order to join the overlay, the Joining Node MUST contact a node in the overlay. Typically this means contacting the bootstrap nodes, since they are reachable by the local peer or have public IP addresses. If the Joining Node has cached a list of peers that it has previously been connected with in this overlay, as an optimization it MAY attempt to use one or more of them as bootstrap nodes before falling back to the bootstrap nodes listed in the configuration file.

When contacting a bootstrap node, the Joining Node MUST first form the DTLS or TLS connection to the bootstrap node and then send an Attach request over this connection with the destination Resource-ID set to the Joining Node's Node-ID plus 1.

When the requester node finally does receive a response from some responding node, it MUST use the Node-ID in the response to start sending requests to join the Overlay Instance as described in Section 6.4.

After a node has successfully joined the overlay network, it will have direct connections to several peers. Some MAY be added to the cached bootstrap nodes list and used in future boots. Peers that are not directly connected MUST NOT be cached. The suggested number of peers to cache is 10. Algorithms for determining which peers to cache are beyond the scope of this specification.

12. Message Flow Example

The following abbreviations are used in the message flow diagrams: JN = Joining Node, AP = Admitting Peer, NP = next peer after the AP, NNP = next next peer which is the peer after NP, PP = previous peer before the AP, PPP = previous previous peer which is the peer before the PP, BP = bootstrap node.

In the following example, we assume that JN has formed a connection to one of the bootstrap nodes. JN then sends an Attach through that peer to a Resource-ID of itself plus 1 (JN+1). It gets routed to the AP, because JN is not yet part of the overlay. When AP responds, JN and the AP use ICE to set up a connection and then set up DTLS. Once AP has connected to JN, AP sends to JN an Update to populate its Routing Table. The following example shows the Update happening after the DTLS connection is formed, but it could also happen before, in which case the Update would often be routed through other nodes.

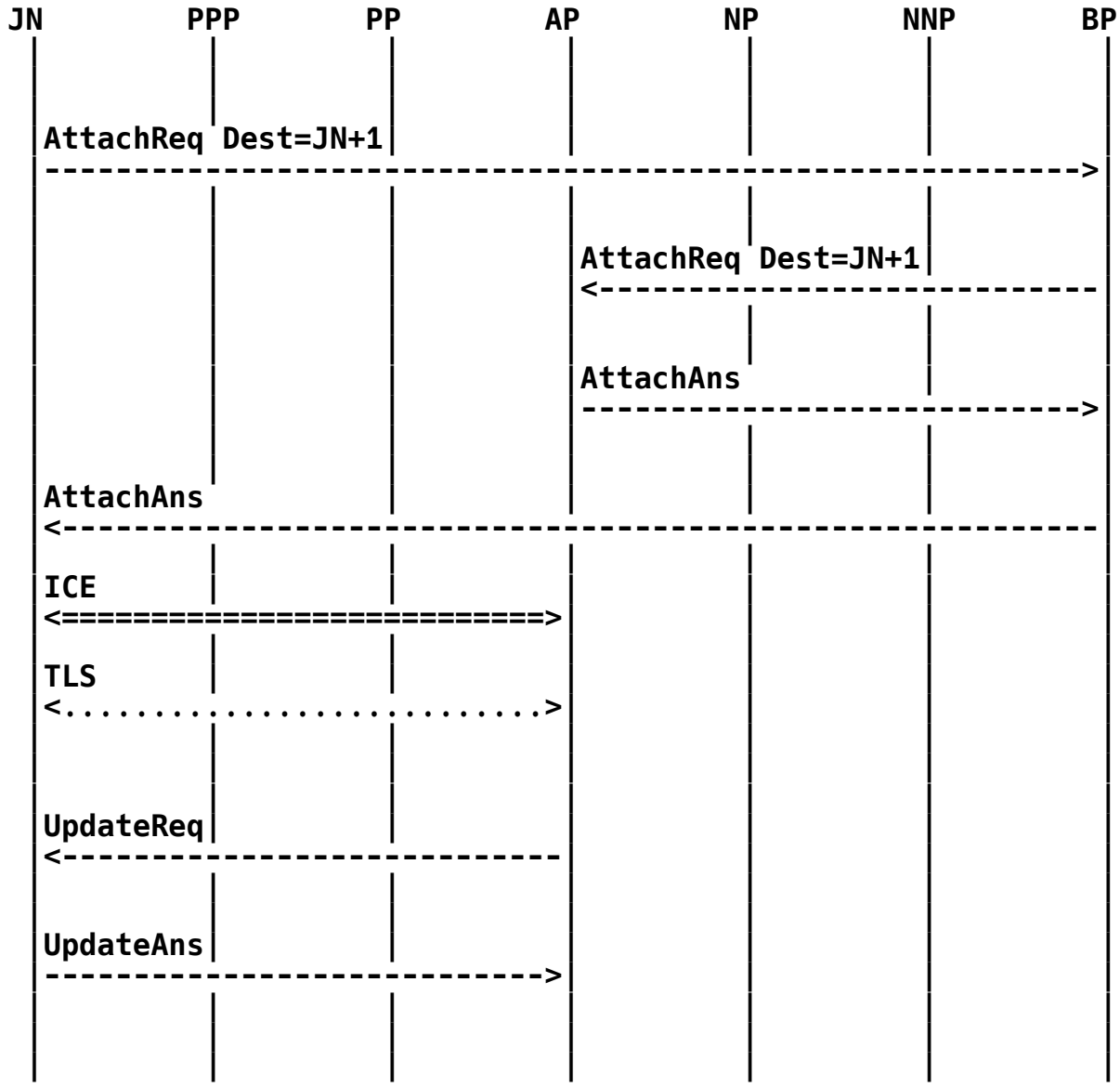

JN
PPP
PP
AP
NP
NNP
BP
AttachReq Dest=JN+1
AttachReq Dest=JN+1
AttachAns
AttachAns
ICE
TLS
UpdateReq
UpdateAns

Figure 1

The JN then forms connections to the appropriate neighbors, such as NP, by sending an Attach which gets routed via other nodes. When NP responds, JN and NP use ICE and DTLS to set up a connection.

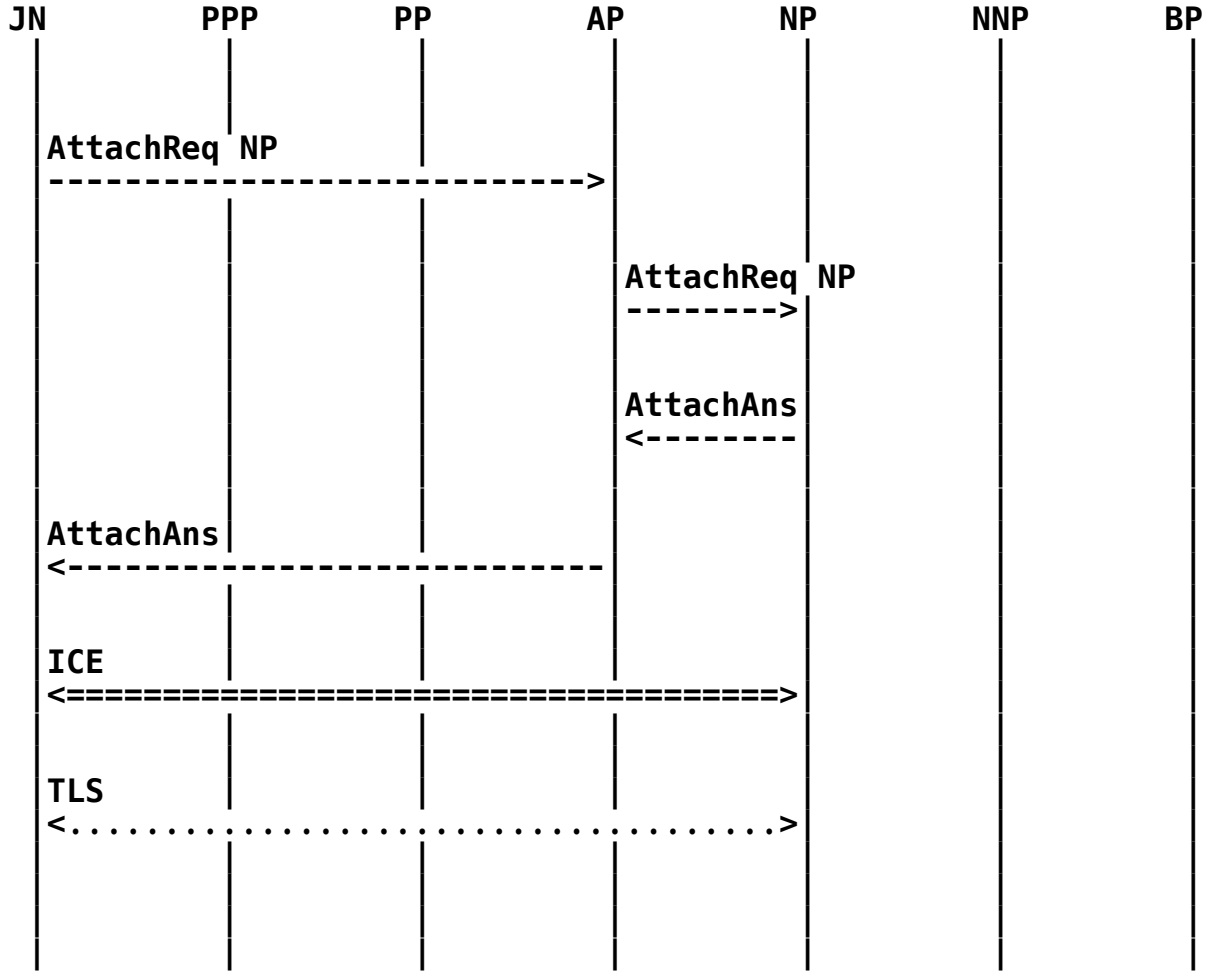


Figure 2

The JN also needs to populate its Finger Table (for the Chord-based DHT). It issues an Attach to a variety of locations around the overlay. The diagram below shows JN sending an Attach halfway around the Chord ring to the JN + 2^127.

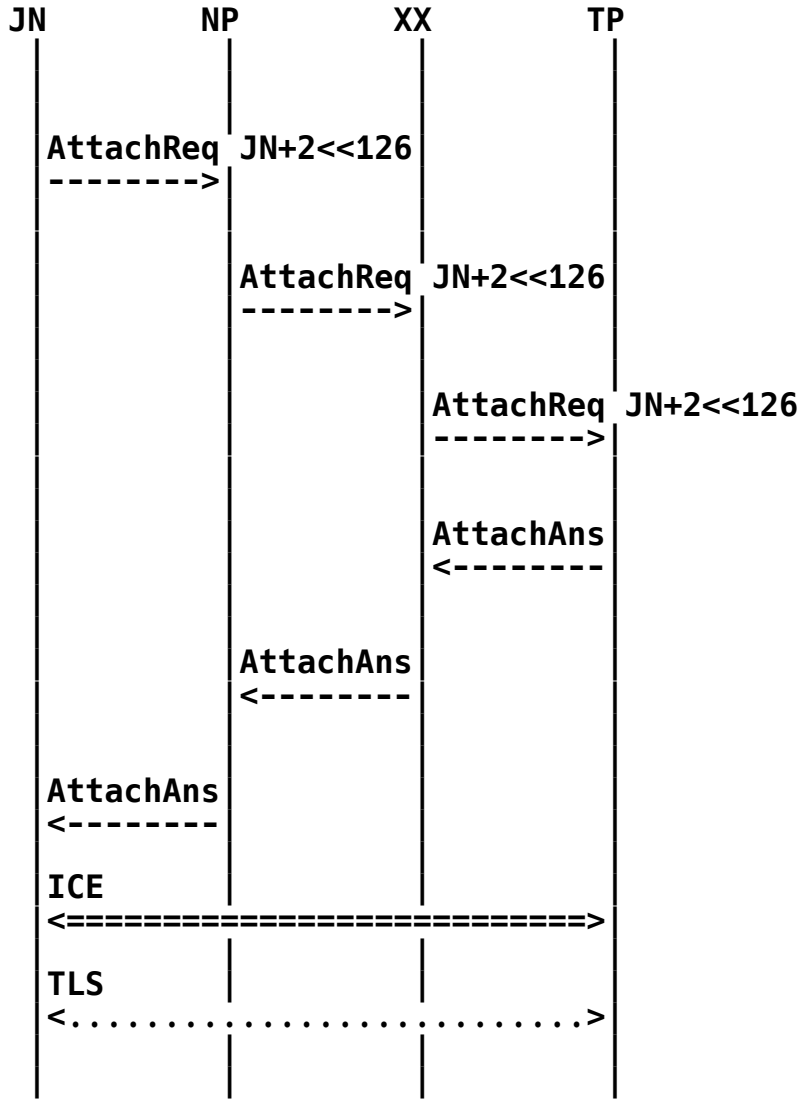


Figure 3

Once JN has a reasonable set of connections, it is ready to take its place in the DHT. It does this by sending a Join to AP. AP sends a series of Store requests to JN to store the data that JN will be responsible for. AP then sends JN an Update that explicitly labels JN as its predecessor. At this point, JN is part of the ring and is responsible for a section of the overlay. AP can now forget any data which is assigned to JN and not to AP.

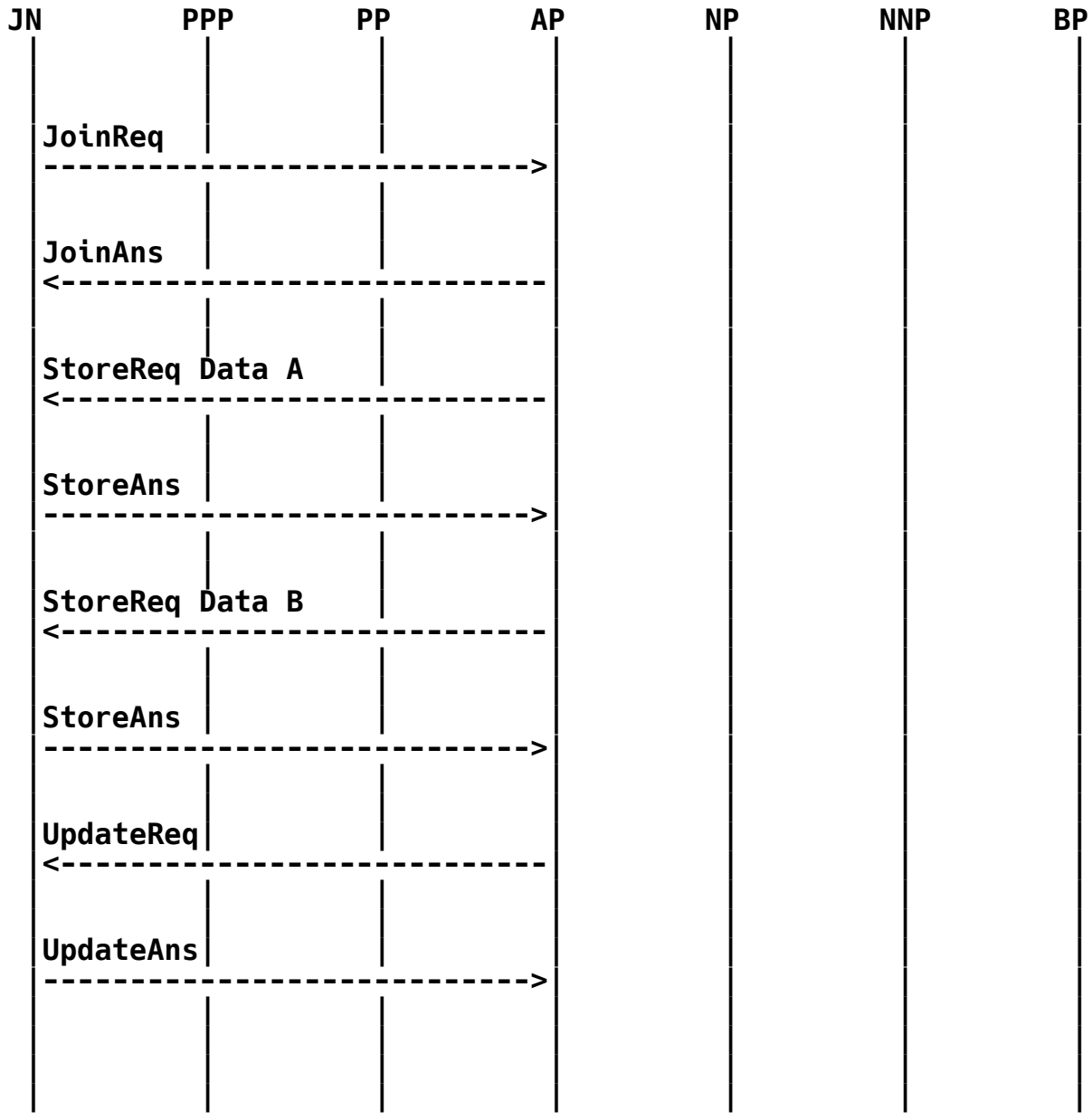
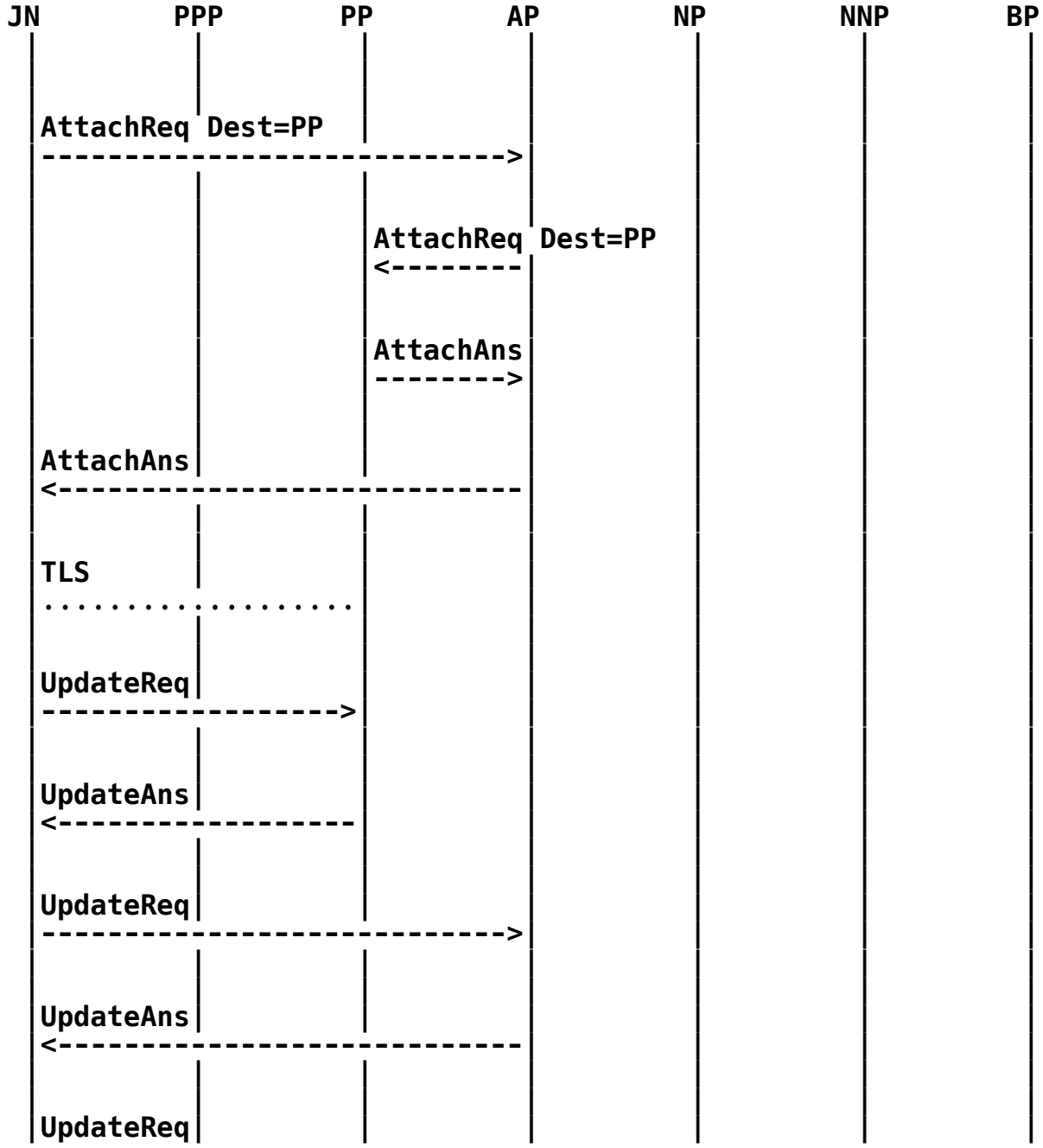


Figure 4

In Chord, JN's Neighbor Table needs to contain its own predecessors. It couldn't connect to them previously, because it did not yet know their addresses. However, now that it has received an Update from AP, as in the previous diagram, it has AP's predecessors, which are also its own, so it sends Attaches to them. Below, it is shown connecting only to AP's closest predecessor, PP.



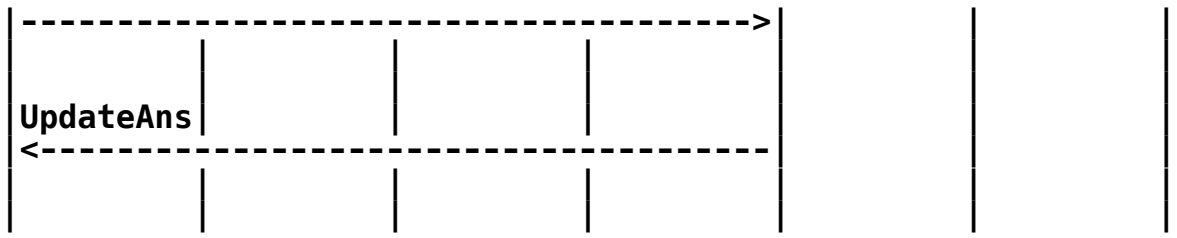


Figure 5

Finally, now that JN has a copy of all the data and is ready to route messages and receive requests, it sends Updates to everyone in its Routing Table to tell them it is ready to go. Below, it is shown sending such an update to TP.

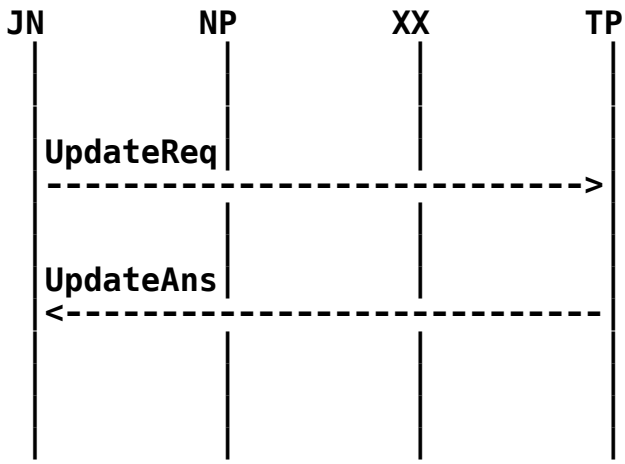


Figure 6

13. Security Considerations

13.1. Overview

RELOAD provides a generic storage service, albeit one designed to be useful for P2PSIP. In this section, we discuss security issues that are likely to be relevant to any usage of RELOAD. More background information can be found in [RFC5765].

In any Overlay Instance, any given user depends on a number of peers with which they have no well-defined relationship except that they are fellow members of the Overlay Instance. In practice, these other nodes may be friendly, lazy, curious, or outright malicious. No security system can provide complete protection in an environment where most nodes are malicious. The goal of security in RELOAD is to

provide strong security guarantees of some properties even in the face of a large number of malicious nodes and to allow the overlay to function correctly in the face of a modest number of malicious nodes.

P2PSIP deployments require the ability to authenticate both peers and resources (users) without the active presence of a trusted entity in the system. We describe two mechanisms. The first mechanism is based on public key certificates and is suitable for general deployments. The second is an admission control mechanism based on an overlay-wide shared symmetric key.

13.2. Attacks on P2P Overlays

The two basic functions provided by overlay nodes are storage and routing: some peer is responsible for storing a node's data and for allowing a third node to fetch this stored data, while other peers are responsible for routing messages to and from the storing nodes. Each of these issues is covered in the following sections.

P2P overlays are subject to attacks by subversive nodes that may attempt to disrupt routing, corrupt or remove user registrations, or eavesdrop on signaling. The certificate-based security algorithms we describe in this specification are intended to protect overlay routing and user registration information in RELOAD messages.

To protect the signaling from attackers pretending to be valid nodes (or nodes other than themselves), the first requirement is to ensure that all messages are received from authorized members of the overlay. For this reason, RELOAD MUST transport all messages over a secure channel (TLS and DTLS are defined in this document) which provides message integrity and authentication of the directly communicating peer. In addition, messages and data MUST be digitally signed with the sender's private key, providing end-to-end security for communications.

13.3. Certificate-Based Security

This specification stores users' registrations and possibly other data in an overlay network. This requires a solution both to securing this data and to securing, as well as possible, the routing in the overlay. Both types of security are based on requiring that every entity in the system (whether user or peer) authenticate cryptographically using an asymmetric key pair tied to a certificate.

When a user enrolls in the Overlay Instance, they request or are assigned a unique name, such as "alice@dht.example.net". These names MUST be unique and are meant to be chosen and used by humans much like a SIP address-of-record (AOR) or an email address. The user

MUST also be assigned one or more Node-IDs by the central enrollment authority. Both the name and the Node-IDs are placed in the certificate, along with the user's public key.

Each certificate enables an entity to act in two sorts of roles:

- As a user, storing data at specific Resource-IDs in the Overlay Instance corresponding to the user name.
- As a overlay peer with the Node-IDs listed in the certificate.

Note that since only users of this Overlay Instance need to validate a certificate, this usage does not require a global Public Key Infrastructure (PKI). Instead, certificates MUST be signed by a central enrollment authority which acts as the certificate authority for the Overlay Instance. This authority signs each node's certificate. Because each node possesses the CA's certificate (which they receive upon enrollment), they can verify the certificates of the other entities in the overlay without further communication. Because the certificates contain the user's/node's public key, communications from the user/node can, in turn, be verified.

If self-signed certificates are used, then the security provided is significantly decreased, since attackers can mount Sybil attacks. In addition, attackers cannot trust the user names in certificates (although they can trust the Node-IDs, because they are cryptographically verifiable). This scheme may be appropriate for some small deployments, such as a small office or an ad hoc overlay set up among participants in a meeting where all hosts on the network are trusted. Some additional security can be provided by using the shared secret admission control scheme as well.

Because all stored data is signed by the owner of the data, the storing node can verify that the storer is authorized to perform a store at that Resource-ID and also can allow any consumer of the data to verify the provenance and integrity of the data when it retrieves it.

Note that RELOAD does not itself provide a revocation/status mechanism (although certificates may, of course, include Online Certificate Status Protocol [OCSP] responder information). Thus, certificate lifetimes SHOULD be chosen to balance the compromise window versus the cost of certificate renewal. Because RELOAD is already designed to operate in the face of some fraction of malicious nodes, this form of compromise is not fatal.

All implementations MUST implement certificate-based security.

13.4. Shared-Secret Security

RELOAD also supports a shared secret admission control scheme that relies on a single key that is shared among all members of the overlay. It is appropriate for small groups that wish to form a private network without complexity. In shared secret mode, all the peers MUST share a single symmetric key which is used to key TLS-PSK or TLS-SRP mode. A peer which does not know the key cannot form TLS connections with any other peer and therefore cannot join the overlay.

One natural approach to a shared-secret scheme is to use a user-entered password as the key. The difficulty with this is that in TLS-PSK mode, such keys are very susceptible to dictionary attacks. If passwords are used as the source of shared keys, then TLS-SRP is a superior choice, because it is not subject to dictionary attacks.

13.5. Storage Security

When certificate-based security is used in RELOAD, any given Resource-ID/Kind-ID pair is bound to some small set of certificates. In order to write data, the writer must prove possession of the private key for one of those certificates. Moreover, all data is stored, signed with the same private key that was used to authorize the storage. This set of rules makes questions of authorization and data integrity, which have historically been thorny for overlays, relatively simple.

13.5.1. Authorization

When a node wants to store some value, it MUST first digitally sign the value with its own private key. It then sends a Store request that contains both the value and the signature towards the storing peer (which is defined by the Resource Name construction algorithm for that particular Kind of value).

When the storing peer receives the request, it MUST determine whether the storing node is authorized to store at this Resource-ID/Kind-ID pair. Determining this requires comparing the user's identity to the requirements of the access control model (see Section 7.3). If it satisfies those requirements, the user is authorized to write, pending quota checks, as described in the next section.

For example, consider a certificate with the following properties:

```
User name: alice@dht.example.com
Node-ID:   013456789abcdef
Serial:    1234
```

If Alice wishes to Store a value of the "SIP Location" Kind, the Resource Name will be the SIP AOR "sip:alice@dht.example.com". The Resource-ID will be determined by hashing the Resource Name. Because SIP Location uses the USER-NODE-MATCH policy, it first verifies that the user name in the certificate hashes to the requested Resource-ID. It then verifies that the Node-ID in the certificate matches the dictionary key being used for the store. If both of these checks succeed, the Store is authorized. Note that because the access control model is different for different Kinds, the exact set of checks will vary.

13.5.2. Distributed Quota

Being a peer in an Overlay Instance carries with it the responsibility to store data for a given region of the Overlay Instance. However, allowing nodes to store unlimited amounts of data would create unacceptable burdens on peers and would also enable trivial denial-of-service (DoS) attacks. RELOAD addresses this issue by requiring configurations to define maximum sizes for each Kind of stored data. Attempts to store values exceeding this size MUST be rejected. (If peers are inconsistent about this, then strange artifacts will happen when the zone of responsibility shifts and a different peer becomes responsible for overlarge data.) Because each Resource-ID/Kind-ID pair is bound to a small set of certificates, these size restrictions also create a distributed quota mechanism, with the quotas administered by the central configuration server.

Allowing different Kinds of data to have different size restrictions allows new usages the flexibility to define limits that fit their needs without requiring all usages to have expansive limits.

13.5.3. Correctness

Because each stored value is signed, it is trivial for any retrieving node to verify the integrity of the stored value. More care needs to be taken to prevent version rollback attacks. Rollback attacks on storage are prevented by the use of store times and lifetime values in each store. A lifetime represents the latest time at which the data is valid and thus limits (although does not completely prevent) the ability of the storing node to perform a rollback attack on retrievers. In order to prevent a rollback attack at the time of the Store request, it is REQUIRED that storage times be monotonically increasing. Storing peers MUST reject Store requests with storage times smaller than or equal to those that they are currently storing. In addition, a fetching node which receives a data value with a storage time older than the result of the previous fetch knows that a rollback has occurred.

13.5.4. Residual Attacks

The mechanisms described here provide a high degree of security, but some attacks remain possible. Most simply, it is possible for storing peers to refuse to store a value (i.e., they reject any request). In addition, a storing peer can deny knowledge of values which it has previously accepted. To some extent, these attacks can be ameliorated by attempting to store to and retrieve from replicas, but a retrieving node does not know whether or not it should try this, as there is a cost to doing so.

The certificate-based authentication scheme prevents a single peer from being able to forge data owned by other peers. Furthermore, although a subversive peer can refuse to return data resources for which it is responsible, it cannot return forged data, because it cannot provide authentication for such registrations. Therefore, parallel searches for redundant registrations can mitigate most of the effects of a compromised peer. The ultimate reliability of such an overlay is a statistical question based on the replication factor and the percentage of compromised peers.

In addition, when a Kind is multivalued (e.g., an array data model), the storing peer can return only some subset of the values, thus biasing its responses. This can be countered by using single values rather than sets, but that makes coordination between multiple storing agents much more difficult. This is a trade-off that must be made when designing any usage.

13.6. Routing Security

Because the storage security system guarantees (within limits) the integrity of the stored data, routing security focuses on stopping the attacker from performing a DoS attack that misroutes requests in the overlay. There are a few obvious observations to make about this. First, it is easy to ensure that an attacker is at least a valid node in the Overlay Instance. Second, this is a DoS attack only. Third, if a large percentage of the nodes on the Overlay Instance are controlled by the attacker, it is probably impossible to perfectly secure against this.

13.6.1. Background

In general, attacks on DHT routing are mounted by the attacker arranging to route traffic through one or two nodes that it controls. In the Eclipse attack [Eclipse], the attacker tampers with messages to and from nodes for which it is on-path with respect to a given victim node. This allows it to pretend to be all the nodes that are reachable through it. In the Sybil attack [Sybil], the attacker registers a large number of nodes and is therefore able to capture a large amount of the traffic through the DHT.

Both the Eclipse and Sybil attacks require the attacker to be able to exercise control over her Node-IDs. The Sybil attack requires the creation of a large number of peers. The Eclipse attack requires that the attacker be able to impersonate specific peers. In both cases, RELOAD attempts to mitigate these attacks by the use of centralized, certificate-based admission control.

13.6.2. Admissions Control

Admission to a RELOAD Overlay Instance is controlled by requiring that each peer have a certificate containing its Node-ID. The requirement to have a certificate is enforced by using certificate-based mutual authentication on each connection. (Note: the following applies only when self-signed certificates are not used.) Whenever a peer connects to another peer, each side automatically checks that the other has a suitable certificate. These Node-IDs MUST be randomly assigned by the central enrollment server. This has two benefits:

- It allows the enrollment server to limit the number of Node-IDs issued to any individual user.

- It prevents the attacker from choosing specific Node-IDs.

The first property allows protection against Sybil attacks (provided that the enrollment server uses strict rate-limiting policies). The second property deters but does not completely prevent Eclipse attacks. Because an Eclipse attacker must impersonate peers on the other side of the attacker, the attacker must have a certificate for suitable Node-IDs, which requires him to repeatedly query the enrollment server for new certificates, which will match only by chance. From the attacker's perspective, the difficulty is that if the attacker has only a small number of certificates, the region of the Overlay Instance he is impersonating appears to be very sparsely populated by comparison to the victim's local region.

13.6.3. Peer Identification and Authentication

In general, whenever a peer engages in overlay activity that might affect the Routing Table, it must establish its identity. This happens in two ways. First, whenever a peer establishes a direct connection to another peer, it authenticates via certificate-based mutual authentication. All messages between peers are sent over this protected channel, and therefore the peers can verify the data origin of the last-hop peer for requests and responses without further cryptography.

In some situations, however, it is desirable to be able to establish the identity of a peer with whom one is not directly connected. The most natural case is when a peer Updates its state. At this point, other peers may need to update their view of the overlay structure, but they need to verify that the Update message came from the actual peer rather than from an attacker. To prevent having a peer accept Update messages from an attacker, all overlay routing messages are signed by the peer that generated them.

For messages that impact the topology of the overlay, replay is typically prevented by having the information come directly from, or be verified by, the nodes that claimed to have generated the update. Data storage replay detection is done by signing the time of the node that generated the signature on the Store request, thus providing a time-based replay protection, but the time synchronization is needed only between peers that can write to the same location.

13.6.4. Protecting the Signaling

The goal here is to stop an attacker from knowing who is signaling what to whom. An attacker is unlikely to be able to observe the activities of a specific individual, given the randomization of IDs and routing based on the present peers discussed above. Furthermore, because messages can be routed using only the header information, the actual body of the RELOAD message can be encrypted during transmission.

There are two lines of defense here. The first is the use of TLS or DTLS for each communications link between peers. This provides protection against attackers who are not members of the overlay. The second line of defense is to digitally sign each message. This prevents adversarial peers from modifying messages in flight, even if they are on the routing path.

13.6.5. Routing Loops and DoS Attacks

Source-routing mechanisms are known to create the possibility for DoS amplification, especially by the induction of routing loops [RFC5095]. In order to limit amplification, the initial-ttl value in the configuration file SHOULD be set to a value slightly larger than the longest expected path through the network. For Chord, experience has shown that log(2) of the number of nodes in the network + 5 is a safe bound. Because nodes are required to enforce the initial-ttl as the maximum value, an attacker cannot achieve an amplification factor greater than initial-ttl, thus limiting the additional capabilities provided by source routing.

In order to prevent the use of loops for targeted implementation attacks, implementations SHOULD check the Destination List for duplicate entries and discard such records with an "Error_Invalid_Message" error. This does not completely prevent loops, but it does require that at least one attacker node be part of the loop.

13.6.6. Residual Attacks

The routing security mechanisms in RELOAD are designed to contain rather than eliminate attacks on routing. It is still possible for an attacker to mount a variety of attacks. In particular, if an attacker is able to take up a position on the overlay routing between A and B, it can make it appear as if B does not exist or is disconnected. It can also advertise false network metrics in an attempt to reroute traffic. However, these are primarily DoS attacks.

The certificate-based security scheme secures the namespace, but if an individual peer is compromised or if an attacker obtains a certificate from the CA, then a number of subversive peers can still appear in the overlay. While these peers cannot falsify responses to resource queries, they can respond with error messages, effecting a DoS attack on the resource registration. They can also subvert routing to other compromised peers. To defend against such attacks, a resource search must still consist of parallel searches for replicated registrations.

14. IANA Considerations

This section contains the new code points registered by this document.

14.1. Well-Known URI Registration

IANA has registered a "well-known URI" as described in [RFC5785]:

URI suffix:	reload-config
Change controller:	IETF <iesg@ietf.org>
Specification document(s):	RFC 6940
Related information:	None

14.2. Port Registrations

IANA has already allocated a TCP port for the main peer-to-peer protocol. This port had the name p2psip-enroll and the port number of 6084. Per this document, IANA has updated this registration to change the service name to reload-config.

IANA has made the following port registration:

Registration Technical Contact	IETF Chair <chair@ietf.org>
Registration Owner	IETF <iesg@ietf.org>
Transport Protocol	TCP
Port Number	6084
Service Name	reload-config
Description	Peer-to-Peer Infrastructure Configuration

14.3. Overlay Algorithm Types

IANA has created a "RELOAD Overlay Algorithm Types" Registry. Entries in this registry are strings denoting the names of overlay algorithms, as described in Section 11.1 of [RFC6940]. The registration policy for this registry is "IETF Review" [RFC522]. The initial contents of this registry are:

Algorithm Name	Reference
CHORD-RELOAD	RFC 6940
EXP-OVERLAY	RFC 6940

The value EXP-OVERLAY has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.4. Access Control Policies

IANA has created a "RELOAD Access Control Policies" Registry. Entries in this registry are strings denoting access control policies, as described in Section 7.3 of [RFC6940]. New entries in this registry SHALL be registered via Standards Action [RFC5226]. The initial contents of this registry are:

Access Policy	Reference
USER-MATCH	RFC 6940
NODE-MATCH	RFC 6940
USER-NODE-MATCH	RFC 6940
NODE-MULTIPLE	RFC 6940
EXP-MATCH	RFC 6940

The value EXP-MATCH has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.5. Application-ID

IANA has created a "RELOAD Application-ID" Registry. Entries in this registry are 16-bit integers denoting Application-IDs, as described in Section 6.5.2 of [RFC6940]. Code points in the range 1 to 32767 SHALL be registered via Standards Action [RFC5226]. Code points in the range 32768 to 61440 SHALL be registered via Expert Review [RFC5226]. Code points in the range 61441 to 65534 are reserved for private use. The initial contents of this registry are:

Application	Application-ID	Specification
INVALID	0	RFC 6940
SIP	5060	Reserved for use by SIP Usage
SIP	5061	Reserved for use by SIP Usage
Reserved	65535	RFC 6940

14.6. Data Kind-ID

IANA has created a "RELOAD Data Kind-ID" registry. Entries in this registry are 32-bit integers denoting data Kinds, as described in Section 5.2 of [RFC6940]. Code points in the range 0x00000001 to 0x7FFFFFFF SHALL be registered via Standards Action [RFC5226]. Code points in the range 0x8000000 to 0xF0000000 SHALL be registered via Expert Review [RFC5226]. Code points in the range 0xF0000001 to 0xFFFFFFFE are reserved for private use via the Kind description mechanism described in Section 11 of [RFC6940]. The initial contents of this registry are:

Kind	Kind-ID	Reference
INVALID	0x0	RFC 6940
TURN-SERVICE	0x2	RFC 6940
CERTIFICATE_BY_NODE	0x3	RFC 6940
CERTIFICATE_BY_USER	0x10	RFC 6940
Reserved	0x7fffffff	RFC 6940
Reserved	0xfffffffe	RFC 6940

14.7. Data Model

IANA has created a "RELOAD Data Model" registry. Entries in this registry are strings denoting data models, as described in Section 7.2 of [RFC6940]. New entries in this registry SHALL be registered via Standards Action [RFC5226]. The initial contents of this registry are:

Data Model	Reference
INVALID	RFC 6940
SINGLE	RFC 6940
ARRAY	RFC 6940
DICTIONARY	RFC 6940
EXP-DATA	RFC 6940
RESERVED	RFC 6940

The value EXP-DATA has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.8. Message Codes

IANA has created a "RELOAD Message Codes" registry. Entries in this registry are 16-bit integers denoting method codes, as described in Section 6.3.3 of [RFC6940]. These codes SHALL be registered via Standards Action [RFC5226]. The initial contents of this registry are:

Message Code Name	Code Value	Reference
invalidMessageCode	0x0	RFC 6940
probe_req	0x1	RFC 6940
probe_ans	0x2	RFC 6940
attach_req	0x3	RFC 6940
attach_ans	0x4	RFC 6940
Unassigned	0x5	
Unassigned	0x6	
store_req	0x7	RFC 6940
store_ans	0x8	RFC 6940
fetch_req	0x9	RFC 6940
fetch_ans	0xA	RFC 6940
Unassigned (was remove_req)	0xB	RFC 6940
Unassigned (was remove_ans)	0xC	RFC 6940
find_req	0xD	RFC 6940
find_ans	0xE	RFC 6940
join_req	0xF	RFC 6940
join_ans	0x10	RFC 6940
leave_req	0x11	RFC 6940
leave_ans	0x12	RFC 6940
update_req	0x13	RFC 6940
update_ans	0x14	RFC 6940
route_query_req	0x15	RFC 6940
route_query_ans	0x16	RFC 6940
ping_req	0x17	RFC 6940
ping_ans	0x18	RFC 6940
stat_req	0x19	RFC 6940
stat_ans	0x1A	RFC 6940
Unassigned (was attachlite_req)	0x1B	RFC 6940
Unassigned (was attachlite_ans)	0x1C	RFC 6940
app_attach_req	0x1D	RFC 6940
app_attach_ans	0x1E	RFC 6940
Unassigned (was app_attachlite_req)	0x1F	RFC 6940
Unassigned (was app_attachlite_ans)	0x20	RFC 6940
config_update_req	0x21	RFC 6940
config_update_ans	0x22	RFC 6940
exp_a_req	0x23	RFC 6940
exp_a_ans	0x24	RFC 6940
exp_b_req	0x25	RFC 6940
exp_b_ans	0x26	RFC 6940
Reserved	0x8000..0xFFFE	RFC 6940
error	0xFFFF	RFC 6940

The values exp_a_req, exp_a_ans, exp_b_req, and exp_b_ans have been made available for the purposes of experimentation. These values are not meant for vendor-specific use of any sort, and they MUST NOT be used for operational deployments.

14.9. Error Codes

IANA has created a "RELOAD Error Code" registry. Entries in this registry are 16-bit integers denoting error codes, as described in Section 6.3.3.1 of [RFC6940]. New entries SHALL be defined via Standards Action [RFC5226]. The initial contents of this registry are:

Error Code Name	Code Value	Reference
invalidErrorCode	0x0	RFC 6940
Unassigned	0x1	
Error_Forbidden	0x2	RFC 6940
Error_Not_Found	0x3	RFC 6940
Error_Request_Timeout	0x4	RFC 6940
Error_Generation_Counter_Too_Low	0x5	RFC 6940
Error_Incompatible_with_Overlay	0x6	RFC 6940
Error_Unsupported_Forwarding_Option	0x7	RFC 6940
Error_Data_Too_Large	0x8	RFC 6940
Error_Data_Too_Old	0x9	RFC 6940
Error_TTL_Exceeded	0xA	RFC 6940
Error_Message_Too_Large	0xB	RFC 6940
Error_Unknown_Kind	0xC	RFC 6940
Error_Unknown_Extension	0xD	RFC 6940
Error_Response_Too_Large	0xE	RFC 6940
Error_Config_Too_Old	0xF	RFC 6940
Error_Config_Too_New	0x10	RFC 6940
Error_In_Progress	0x11	RFC 6940
Error_Exp_A	0x12	RFC 6940
Error_Exp_B	0x13	RFC 6940
Error_Invalid_Message	0x14	RFC 6940
Reserved	0x8000..0xFFFE	RFC 6940

The values Error_Exp_A and Error_Exp_B have been made available for the purposes of experimentation. These values are not meant for vendor-specific use of any sort, and they MUST NOT be used for operational deployments.

14.10. Overlay Link Types

IANA has created a "RELOAD Overlay Link Registry". Entries in this registry are 8-bit integers, as described in Section 6.5.1.1 of [RFC6940]. For more information on the link types defined here, see Section 6.6 of [RFC6940]. New entries SHALL be defined via Standards Action [RFC5226]. This registry has been initially populated with the following values:

Protocol	Code	Reference
INVALID-PROTOCOL	0	RFC 6940
DTLS-UDP-SR	1	RFC 6940
DTLS-UDP-SR-NO-ICE	3	RFC 6940
TLS-TCP-FH-NO-ICE	4	RFC 6940
EXP-LINK	5	RFC 6940
Reserved	255	RFC 6940

The value EXP-LINK has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.11. Overlay Link Protocols

IANA has created a "RELOAD Overlay Link Protocol Registry". Entries in this registry are strings denoting protocols as described in Section 11.1 of this document and SHALL be defined via Standards Action [RFC5226]. This registry has been initially populated with the following values:

Link Protocol	Reference
TLS	RFC 6940
EXP-PROTOCOL	RFC 6940

The value EXP-PROTOCOL has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.12. Forwarding Options

IANA has created a "RELOAD Forwarding Option Registry". Entries in this registry are 8-bit integers denoting options, as described in Section 6.3.2.3 of [RFC6940]. Values between 1 and 127 SHALL be defined via Standards Action [RFC5226]. Entries in this registry between 128 and 254 SHALL be defined via Specification Required [RFC5226]. This registry has been initially populated with the following values:

Forwarding Option	Code	Reference
invalidForwardingOption	0	RFC 6940
exp-forward	1	RFC 6940
Reserved	255	RFC 6940

The value exp-forward has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.13. Probe Information Types

IANA has created a "RELOAD Probe Information Type Registry". Entries are 8-bit integers denoting types as described in Section 6.4.2.5.1 of [RFC6940] and SHALL be defined via Standards Action [RFC5226]. This registry has been initially populated with the following values:

Probe Option	Code	Reference
invalidProbeOption	0	RFC 6940
responsible_set	1	RFC 6940
num_resources	2	RFC 6940
uptime	3	RFC 6940
exp-probe	4	RFC 6940
Reserved	255	RFC 6940

The value exp-probe has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.14. Message Extensions

IANA has created a "RELOAD Extensions Registry". Entries in this registry are 8-bit integers denoting extensions as described in Section 6.3.3 of [RFC6940] and SHALL be defined via Specification Required [RFC5226]. This registry has been initially populated with the following values:

Extensions Name	Code	Reference
invalidMessageExtensionType	0x0	RFC 6940
exp-ext	0x1	RFC 6940
Reserved	0xFFFF	RFC 6940

The value exp-ext has been made available for the purposes of experimentation. This value is not meant for vendor-specific use of any sort, and it MUST NOT be used for operational deployments.

14.15. Reload URI Scheme

This section describes the scheme for a reload URI, which can be used to refer to either:

- A peer, e.g., as used in a certificate (see Section 11.3 of [RFC6940]).
- A resource inside a peer.

The reload URI is defined using a subset of the URI schema specified in Appendix A of RFC 3986 [RFC3986] and the associated URI Guidelines [RFC4395] per the following ABNF syntax:

```
RELOAD-URI = "reload://" destination "@" overlay "/"
         [specifier]
destination = 1*HEXDIG
overlay = reg-name
specifier = 1*HEXDIG
```

The definitions of these productions are as follows:

destination
: A hexadecimal-encoded Destination List object (i.e., multiple concatenated Destination objects with no length prefix prior to the object as a whole).

overlay
The name of the overlay.

specifier
A hexadecimal-encoded StoredDataSpecifier indicating the data element.

If no specifier is present, this URI addresses the peer which can be reached via the indicated Destination List at the indicated overlay name. If a specifier is present, the URI addresses the data value.

14.15.1. URI Registration

The following summarizes the information necessary to register the reload URI.

URI Scheme Name: reload

Status: permanent

URI Scheme Syntax: see Section 14.15 of RFC 6940

URI Scheme Semantics: The reload URI is intended to be used as a reference to a RELOAD peer or resource.

Encoding Considerations: The reload URI is not intended to be human-readable text, so it is encoded entirely in US-ASCII.

Applications/protocols that Use this URI Scheme: The RELOAD protocol described in RFC 6940.

Interoperability Considerations: See RFC 6940.

Security Considerations: See RFC 6940

Contact: Cullen Jennings <fluffy@cisco.com>

Author/Change Controller: IESG

References: RFC 6940

14.16. Media Type Registration

Type Name: application

Subtype Name: p2p-overlay+xml

Required Parameters: none

Optional Parameters: none

Encoding Considerations: Must be binary encoded.

Security Considerations: This media type is typically not used to transport information that needs to be kept confidential. However, there are cases where it is integrity of the information is important. For these cases, using a digital signature is RECOMMENDED. One way of doing this is specified in RFC 6940. In the case when the media includes a shared-secret element, the contents of the file MUST be kept confidential or else anyone who can see the shared secret can affect the RELOAD overlay network.

Interoperability Considerations: No known interoperability consideration beyond those identified for application/xml in [RFC3023].

Published Specification: RFC 6940

Applications that Use this Media Type: The type is used to configure the peer-to-peer overlay networks defined in RFC 6940.

Additional Information: The syntax for this media type is specified in Section 11.1 of [RFC6940]. The contents MUST be valid XML that is compliant with the RELAX NG grammar specified in RFC 6940 and that use the UTF-8[RFC3629] character encoding.

Magic Number(s): none

File Extension(s): relo

Macintosh File Type Code(s): none

Person & Email Address to Contact for Further Information: Cullen Jennings <fluffy@cisco.com>

Intended Usage: COMMON

Restrictions on Usage: None

Author: Cullen Jennings <fluffy@cisco.com>

Change Controller: IESG

14.17. XML Namespace Registration

This document registers two URIs for the config and config-chord XML namespaces in the IETF XML registry defined in [RFC3688].

14.17.1. Config URL

URI: urn:ietf:params:xml:ns:p2p:config-base

Registrant Contact: IESG.

XML: N/A, the requested URIs are XML namespaces

14.17.2. Config Chord URL

URI: urn:ietf:params:xml:ns:p2p:config-chord

Registrant Contact: The IESG.

XML: N/A, the requested URIs are XML namespaces

15. Acknowledgments

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Appendix A. Routing Alternatives

Significant discussion has been focused on the selection of a routing algorithm for P2PSIP. This section discusses the motivations for selecting symmetric recursive routing for RELOAD and describes the extensions that would be required to support additional routing algorithms.

A.1. Iterative vs. Recursive

Iterative routing has a number of advantages. It is easier to debug, consumes fewer resources on intermediate peers, and allows the querying peer to identify and route around misbehaving peers [non-transitive-dhts-worlds05]. However, in the presence of NATs, iterative routing is intolerably expensive, because a new connection must be established for each hop (using ICE) [bryan-design-hotp2p08].

Iterative routing is supported through the RouteQuery mechanism and is primarily intended for debugging. It also allows the querying peer to evaluate the routing decisions made by the peers at each hop, consider alternatives, and perhaps detect at what point the forwarding path fails.

A.2. Symmetric vs. Forward Response

An alternative to the symmetric recursive routing method used by RELOAD is forward-only routing, where the response is routed to the requester as if it were a new message initiated by the responder. (In the previous example, Z sends the response to A as if it were sending a request.) Forward-only routing requires no state in either the message or intermediate peers.

The drawback of forward-only routing is that it does not work when the overlay is unstable. For example, if A is in the process of joining the overlay and is sending a Join request to Z, it is not yet reachable via forward-only routing. Even if it is established in the overlay, if network failures produce temporary instability, A may not be reachable (and may be trying to stabilize its network connectivity via Attach messages).

Furthermore, forward-only responses are less likely to reach the querying peer than symmetric recursive ones are, because the forward path is more likely to have a failed peer than is the request path (which was just tested to route the request) [non-transitive-dhts-worlds05].

An extension to RELOAD that supports forward-only routing but relies on symmetric responses as a fallback would be possible, but due to the complexities of determining when to use forward-only routing and when to fallback to symmetric routing, we have chosen not to include it as an option at this point.

A.3. Direct Response

Another routing option is direct response routing, in which the response is returned directly to the querying node. In the previous example, if A encodes its IP address in the request, then Z can simply deliver the response directly to A. In the absence of NATs or other connectivity issues, this is the optimal routing technique.

The challenge of implementing direct response routing is the presence of NATs. There are a number of complexities that must be addressed. In this discussion, we will continue our assumption that A issued the request and Z is generating the response.

- The IP address listed by A may be unreachable, either due to NAT or firewall rules. Therefore, a direct response technique must fallback to symmetric response [non-transitive-dhts-worlds05]. The hop-by-hop ACKs used by RELOAD allow Z to determine when A has received the message (and the TLS negotiation will provide earlier confirmation that A is reachable), but this fallback requires a timeout that will increase the response latency whenever A is not reachable from Z.

- Whenever A is behind a NAT it, will have multiple candidate IP addresses, each of which must be advertised to ensure connectivity. Therefore, Z will need to attempt multiple connections to deliver the response.

- One (or all) of A's candidate addresses may route from Z to a different device on the Internet. In the worst case, these nodes may actually be running RELOAD on the same port. Therefore, it is absolutely necessary to establish a secure connection to authenticate A before delivering the response. This step diminishes the efficiency of direct response routing, because multiple round-trips are required before the message can be delivered.

- If A is behind a NAT and does not have a connection already established with Z, there are only two ways the direct response will work. The first is that A and Z must both be behind the same NAT, in which case the NAT is not involved. In the more common case, when Z is outside A's NAT, the response will be received only if A's NAT implements endpoint-independent filtering. As the

choice of filtering mode conflates application transparency with security [RFC4787] and no clear recommendation is available, the prevalence of this feature in future devices remains unclear.

An extension to RELOAD that supports direct response routing but relies on symmetric responses as a fallback would be possible, but due to the complexities of determining when to use direct response routing and when to fallback to symmetric routing, and the reduced performance for responses to peers behind restrictive NATs, we have chosen not to include it as an option at this point.

A.4. Relay Peers

[P2PSIP-RELAY] has proposed implementing a form of direct response by having A identify a peer, Q, that will be directly reachable by any other peer. A uses Attach to establish a connection with Q and advertises Q's IP address in the request sent to Z. Z sends the response to Q, which relays it to A. This then reduces the latency to two hops, and Z is negotiating a secure connection to Q.

This technique relies on the relative population of nodes such as A that require relay peers and peers such as Q that are capable of serving as a relay peer. It also requires nodes to be able to identify which category they are in. This identification problem has turned out to be hard to solve and is still an open area of exploration.

An extension to RELOAD that supports relay peers is possible, but due to the complexities of implementing such an alternative, we have not added such a feature to RELOAD at this point.

A concept similar to relay peers, essentially choosing a relay peer at random, has previously been suggested to solve problems of pair-wise non-transitivity [non-transitive-dhts-worlds05], but deterministic filtering provided by NATs makes random relay peers no more likely to work than the responding peer.

A.5. Symmetric Route Stability

A common concern about symmetric recursive routing has been that one or more peers along the request path may fail before the response is received. The significance of this problem essentially depends on the response latency of the overlay. An overlay that produces slow responses will be vulnerable to churn, whereas responses that are delivered very quickly are vulnerable only to failures that occur over that small interval.

The other aspect of this issue is whether the request itself can be successfully delivered. Assuming typical connection maintenance intervals, the time period between the last maintenance and the request being sent will be orders of magnitude greater than the delay between the request being forwarded and the response being received. Therefore, if the path was stable enough to be available to route the request, it is almost certainly going to remain available to route the response.

An overlay that is unstable enough to suffer this type of failure frequently is unlikely to be able to support reliable functionality regardless of the routing mechanism. However, regardless of the stability of the return path, studies show that in the event of high churn, iterative routing is a better solution to ensure request completion [lookups-churn-p2p06] [non-transitive-dhts-worlds05]

Finally, because RELOAD retries the end-to-end request, that retry will address the issues of churn that remain.

Appendix B. Why Clients?

There are a wide variety of reasons a node may act as a client rather than as a peer. This section outlines some of those scenarios and how the client's behavior changes based on its capabilities.

B.1. Why Not Only Peers?

For a number of reasons, a particular node may be forced to act as a client even though it is willing to act as a peer. These include:

- The node does not have appropriate network connectivity, typically because it has a low-bandwidth network connection.
- The node may not have sufficient resources, such as computing power, storage space, or battery power.
- The overlay algorithm may dictate specific requirements for peer selection. These may include participating in the overlay to determine trustworthiness, controlling the number of peers in the overlay to reduce overly long routing paths, and ensuring minimum application uptime before a node can join as a peer.

The ultimate criteria for a node to become a peer are determined by the overlay algorithm and specific deployment. A node acting as a client that has a full implementation of RELOAD and the appropriate overlay algorithm is capable of locating its responsible peer in the overlay and using Attach to establish a direct connection to that peer. In that way, it may elect to be reachable under either of the

routing approaches listed above. Particularly for overlay algorithms that elect nodes to serve as peers based on trustworthiness or population, the overlay algorithm may require such a client to locate itself at a particular place in the overlay.

B.2. Clients as Application-Level Agents

SIP defines an extensive protocol for registration and security between a client and its registrar/proxy server(s). Any SIP device can act as a client of a RELOAD-based P2PSIP overlay if it contacts a peer that implements the server-side functionality required by the SIP protocol. In this case, the peer would be acting as if it were the user's peer and would need the appropriate credentials for that user.

Application-level support for clients is defined by a usage. A usage offering support for application-level clients should specify how the security of the system is maintained when the data is moved between the application and RELOAD layers.

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