ICNRG
Internet-Draft
Intended status: Experimental
Expires: September 28, 2017

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ICN Traceroute Protocol Specification
draft-mastorakis-icnrg-icntraceroute-01

Abstract

This document presents the design of an ICN Traceroute protocol. This includes the operations both on the client and the forwarder side. The design expresses the views of the authors and does not represent the views of the Named Data Networking Project Team.

Status of This Memo

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1. Introduction

In TCP/IP, routing and forwarding are based on IP addresses. To determine the route to an IP address and to measure the transit delays, the traceroute utility is used. In ICN, routing and forwarding are based on name prefixes. To this end, the problem of determining the characteristics (i.e., transit forwarders and delays) of, at least, one of the available routes to a name prefix is fundamendal.

This document proposes protocol mechanisms for a traceroute equivalent in ICN networks. This document contains two appendix sections: 1) A non-normative appendix section suggesting useful properties for an ICN traceroute client application that originates traceroute requests and processes traceroute replies and 2) An appendix section summarizing the open questions of the current protocol design.

1.1. 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 [RFC2119].

2. Background on IP-Based Traceroute Operation

In IP-based networks, traceroute is based on the expiration of the Time To Live (TTL) IP header field. Specifically, a traceroute client sends consecutive packets (depending on the implementation and the user-specified behavior such packets can be either UDP datagrams, ICMP Echo Request or TCP SYN packets) with a TTL value increased by 1, essentially, performing a expanding ring search. In this way, the first IP packet sent will expire at the first router along the path, the second IP packet at the second router along the path, etc, until the router with the specified destination IP address is reached. Each router along the path towards the destination will respond by sending back an ICMP Time Exceeded packet.

The IP-based traceroute utility operates on IP addresses, and in particular depends on the IP packets having source IP addresses that are used as the destination address for replies. Given that ICN forwards based on names rather than destination IP addresses, that the names do not refer to unique endpoints (multi-destination), and that the packets do not contain source addresses, a different approach is clearly needed.

3. Traceroute Functionality Challenges and Opportunities in ICN

In NDN and CCN protocols, the communication paradigm is based exclusively on named objects. An Interest is forwarded across the network based on its name. Eventually, it retrieves a content object either from a producer application or some forwarder’s Content Store (CS).

An ICN network differs from an IP network in at least 4 important ways:

- IP identifies interfaces to an IP network with a fixed-length number, and delivers IP packets to one or more interfaces. ICN identifies units of data in the network with a variable length name consisting of a list of components.

- An IP-based network depends on the IP packets having source IP addresses that are used as the destination address for replies. On the other hand, ICN Interests do not have source addresses and they are forwarded based on names, which do not refer to a unique

end-point. Data packets follow the reverse path of the Interests based on hop-by-hop state created during Interest forwarding.

- An IP network supports multi-path, single destination, stateless packet forwarding and delivery via unicast, a limited form of multi-destination selected delivery with anycast, and group-based multi-destination delivery via multicast. In contrast, ICN supports multi-path and multi-destination stateful Interest forwarding and multi-destination data delivery to units of named data. This single forwarding semantic subsumes the functions of unicast, anycast, and multicast. As a result, consecutive (or retransmitted) ICN Interest messages may be forwarded through an ICN network along different paths, and may be forwarded to different data sources (e.g., end-node applications, in-network storage) holding a copy of the requested unit of data. The property of discovering multiple available (or potentially all) paths towards a name prefix may be desirable for an ICN traceroute protocol, since it can be beneficial for congestion control purposes. Knowing the number of available paths for a name can also be useful in cases that Interest forwarding based on application semantics/preferences is desirable.

- In the case of multiple Interests with the same name arriving at a forwarder, a number of Interests may be aggregated in a common Pending Interest Table (PIT) entry. Depending on the lifetime of a PIT entry, the round-trip time an Interest-Data exchange might significantly vary (e.g., it might be shorter than the full round-trip time to reach the original content producer). To this end, the round-trip time experienced by consumers might also vary.

These differences introduce new challenges, new opportunities and new requirements in the design of ICN traceroute. Following this communication model, a traceroute client should be able to express traceroute requests with some name prefix and receive responses.

Our goals are the following:

- Trace one or more paths towards an ICN forwarder (for troubleshooting purposes).

- Trace one or more paths along which an application can be reached in the sense that Interest packets can be forwarded towards it.

- Test whether a specific named object is cached in some on-path CS, and, if so, trace the path towards it and return the corresponding forwarder.

- Perform transit delay network measurements.

To this end, a traceroute target name can represent:

- An administrative name that has been assigned to a forwarder. Assigning a name to a forwarder requires a management application running locally, which handles Operations, Administration and Management (OAM) operations.

- A name that includes an application’s namespace as a prefix.

- A named object that might reside in some in-network storage.

In order to provide stable and reliable diagnostics, it is desirable that the packet encoding of a traceroute request enables the forwarders to distinguish this request from a normal Interest, while also allowing for forwarding behavior to be as similar as possible to that of an Interest packet. In the same way, the encoding of a traceroute reply should allow for processing similar to that of a data packet by the forwarders.

The term "traceroute session" is used for an iterative process during which an endpoint client application generates a number of traceroute requests to successively traverse more distant hops in the path until it receives a final traceroute reply from a forwarder. It may be desirable that ICN traceroute is able to discover a number of paths towards the expressed prefix within the same session or subsequent sessions. To discover all the hops in a path, we need a mechanism (Interest Steering) to steer requests along different paths.

It is also important, in the case of traceroute requests for the same prefix from different sources, to have a mechanism to avoid aggregating those requests in the PIT. To this end, we need some encoding in the traceroute requests to make each request for a common prefix unique, and hence avoid PIT aggregation and further enabling the exact matching of a response with a particular traceroute packet.

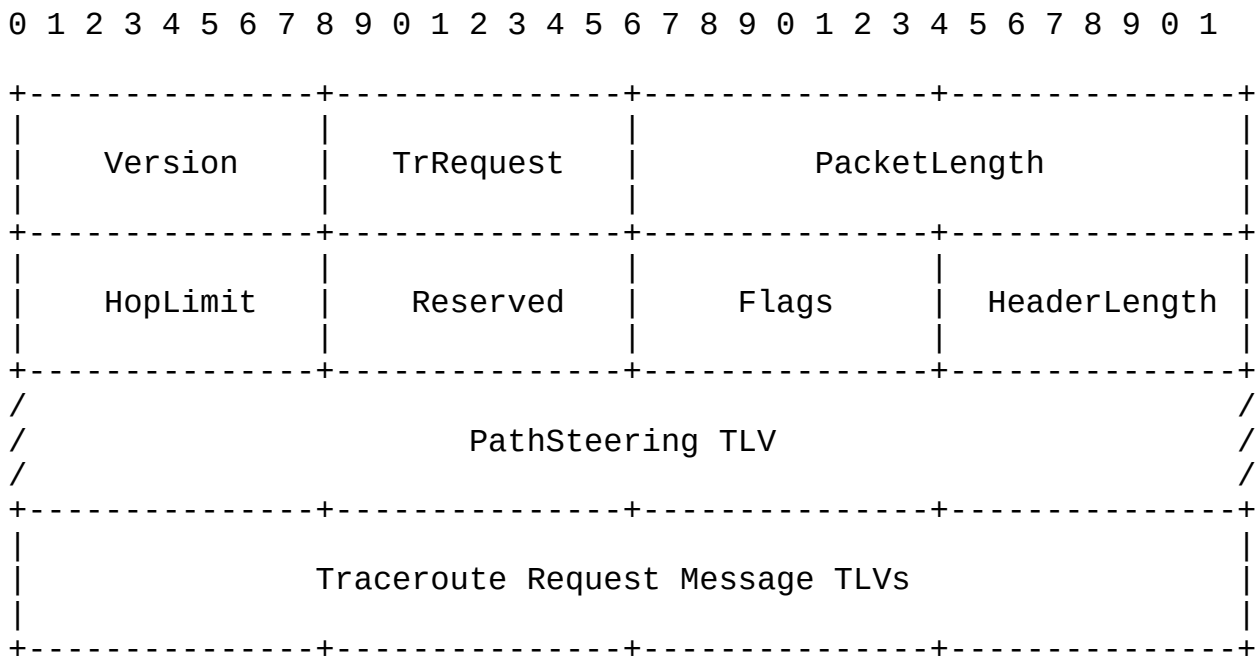
The packet types and format are presented in Section 4. The procedures, e.g. the procedures for determining and indicating that a destination has been reached, are specified in Section 6.

4. ICN Traceroute CCNx Packet Format

In this section, we present the CCNx packet format [CCNMessages] of ICN traceroute, where messages exist within outermost containments (packets). Specifically, we propose two types of traceroute packets, a traceroute request and a reply packet type.

4.1. ICN Traceroute Request CCNx Packet Format

The format of the traceroute request packet is presented below:

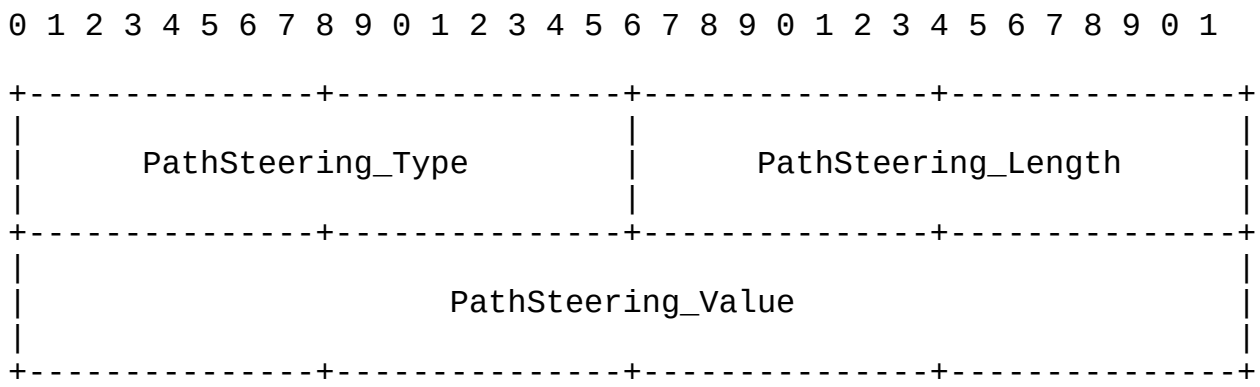


Traceroute Request CCNx Packet Format

The existing packet header fields have similar functionality to the header fields of a CCNx Interest packet. The value of the packet type field is TrRequest. The exact numeric value of this field type is to be determined.

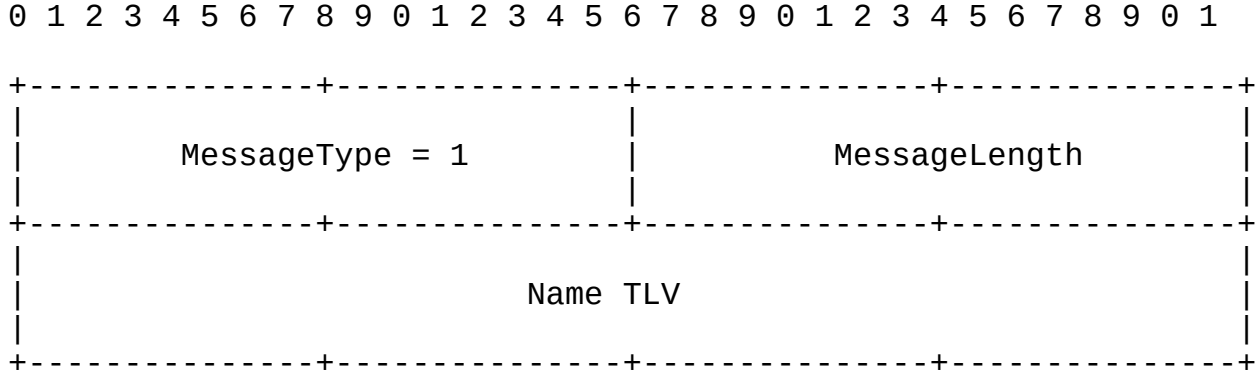
Compared to the typical format of a CCNx packet header [CCNMessages], there is a new optional fixed header TLV added to the packet header:

- A Path Steering hop-by-hop header TLV, which is constructed hop-by-hop in the traceroute reply and included in the traceroute request to steer consecutive requests expressed by a client towards a common or different forwarding paths. An example of such a scheme is presented in [LIPSIN].



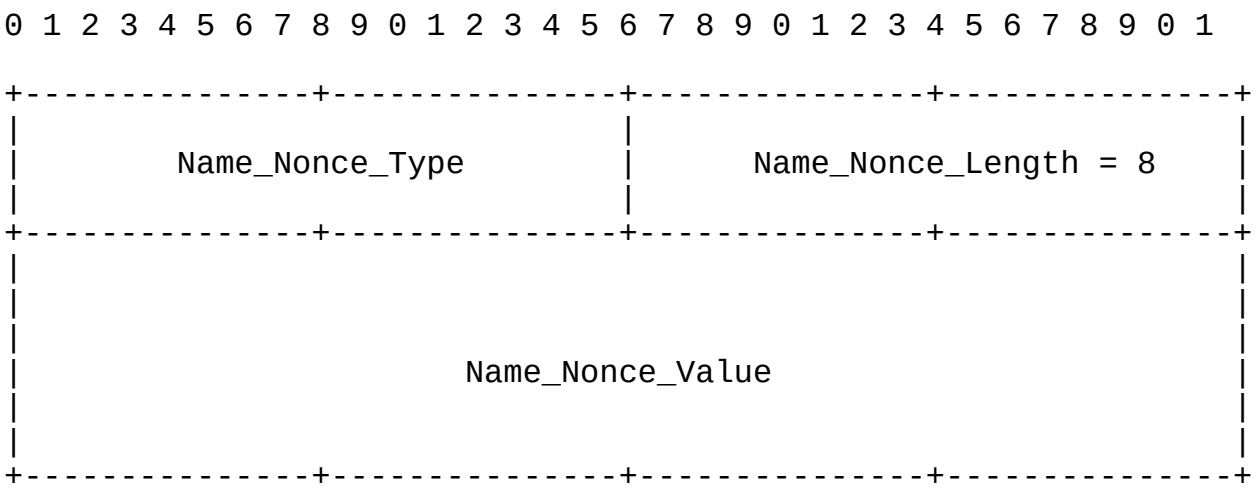
Path Steering TLV

The message of a traceroute request is presented below:



Traceroute Request Message Format

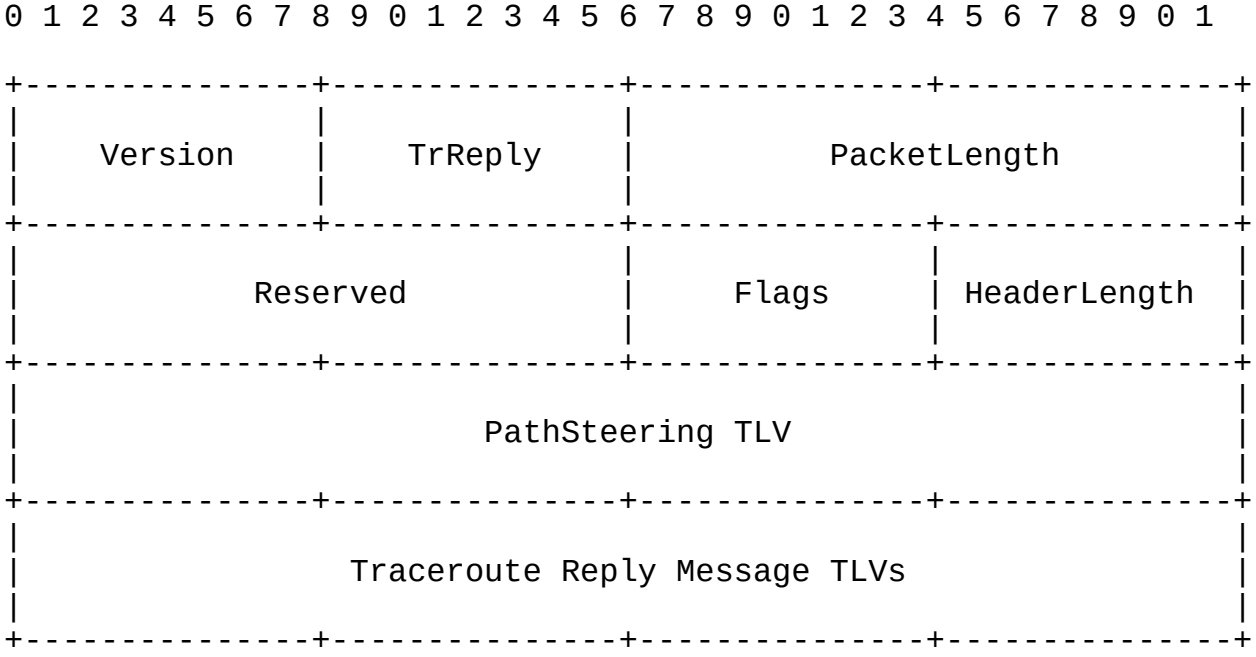
The traceroute request message is of type Interest in order to leverage the Interest forwarding behavior provided by the network. The Name TLV has the structure described in [CCNMessages]. The name consists of the target (destination) prefix appended with a nonce typed name component as its last component (to avoid Interest aggregation and allow exact matching of requests with responses) The value of this TLV will be a 64-bit nonce.



Name Nonce Typed Component TLV

4.2. Traceroute Reply CCNx Packet Format

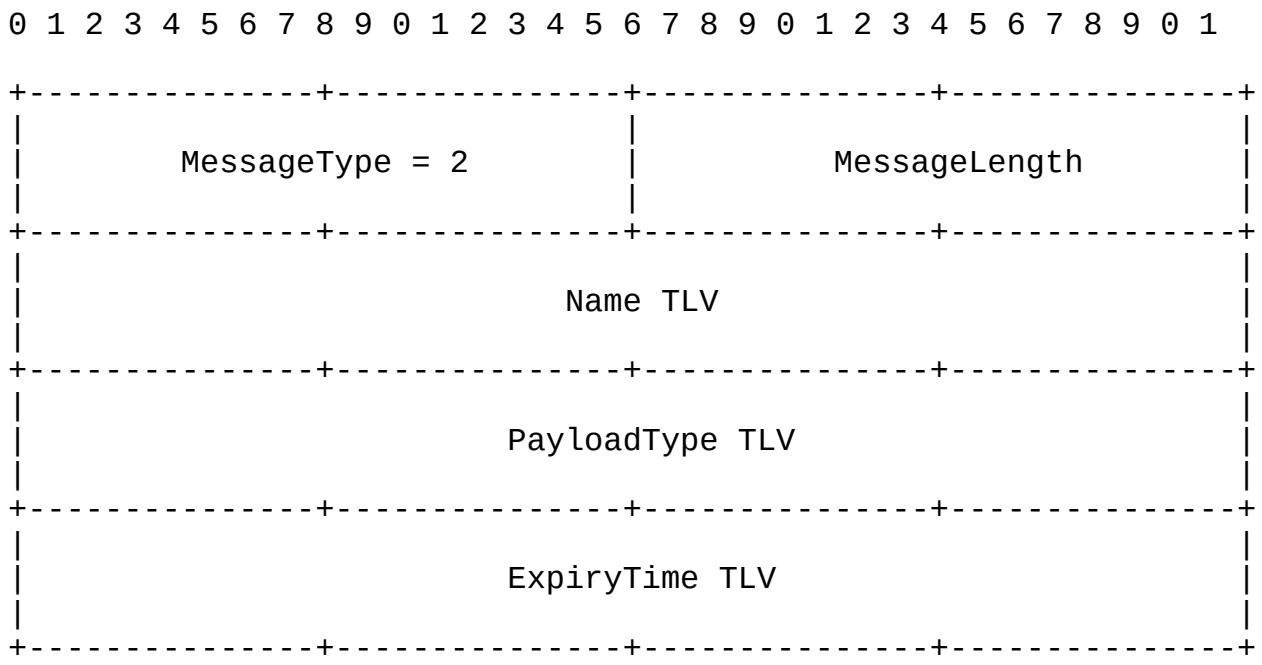
The format of a traceroute reply packet is presented below:



Traceroute Reply CCNx Packet Format

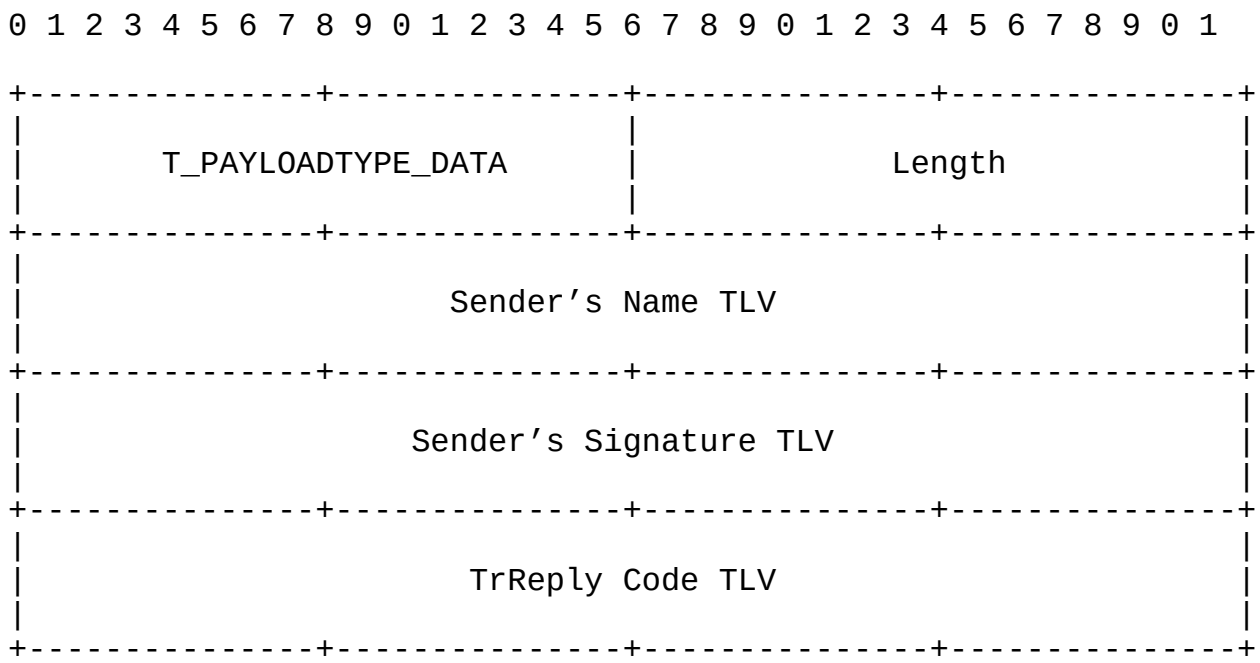
The header of a traceroute reply consists of the header fields of a CCNx Content Object and a hop-by-hop path steering TLV. The value of the packet type field is TrReply. The exact numeric value of this field type is to be determined.

A traceroute reply message is of type Content Object, contains a Name TLV (name of the corresponding traceroute request), a PayloadType TLV and an ExpiryTime TLV with a value of 0 to indicate that replies must not be cached by the network.



Traceroute Reply Message Format

The PayloadType TLV is presented below. It is of type T_PAYLOADTYPE_DATA, and the data schema consists of 2 TLVs: 1) the name of the sender of this reply (with the same structure as a CCNx Name TLV), 2) the sender’s signature of their own name (with the same structure as a CCNx ValidationPayload TLV), 3) a TLV with return codes to indicate whether the request was satisfied due to the existence of a local application, a CS hit or a match with a forwarder’s name, or the HopLimit value of the corresponding request reached 0.

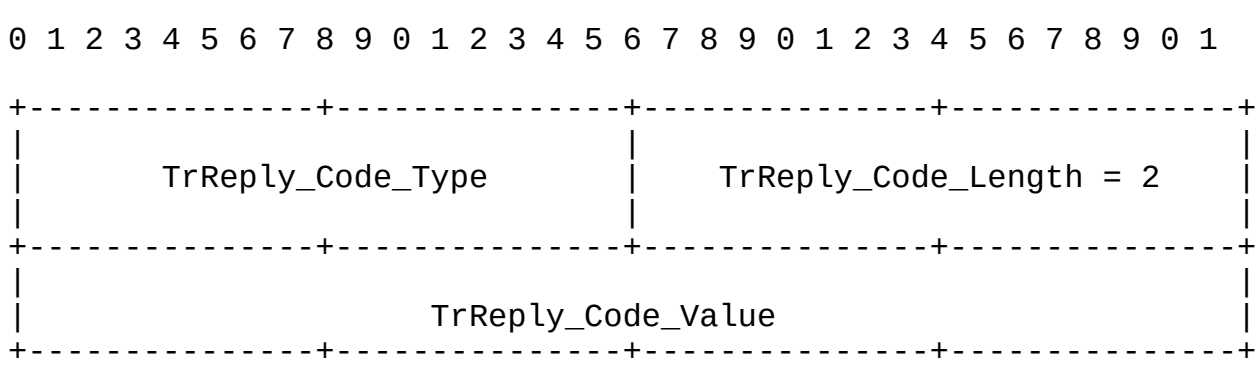


Traceroute Reply Message Format

The goal of including the name of the sender in the reply is to enable the user to reach this entity directly to ask for further management/administrative information using generic Interest-Data exchanges after a successful verification of the sender’s name.

The structure of the TrReply Code TLV is presented below (16-bit value). The potential values are the following:

- 1: Indicates that the target name matched the administrative name of a forwarder (as served by its internal management application).
- 2: Indicates that the target name matched a prefix served by an application (other than the internal management application of a forwarder).
- 3: Indicates that the target name matched the name of an object in a forwarder’s CS.
- 4: Indicates that the the Hop limit reached the 0 value.



TrReply Code TLV

5. ICN Traceroute NDN Packet Format

In this section, we present the ICN traceroute Request and Reply Format according to the NDN packet specification [NDNTLV].

5.1. ICN Traceroute Request NDN Packet Format

A traceroute request is encoded as an NDN Interest packet. Its format is the following:

```
TracerouteRequest ::= INTEREST-TYPE TLV-LENGTH
                      Name
                      MustBeFresh
                      Nonce
                      HopLimit TLV
                      PathSteering TLV?
```

Traceroute Request NDN Packet Format

The name of a request consists of the target name, a nonce value (it can be the value of the Nonce field) and the suffix "traceroute" to denote that this Interest is a traceroute request.

A traceroute request contains 2 new fields. The first one is an optional field for the hop-by-hop PathSteering TLV. The format of this field is the following:

```
PathSteering TLV ::= PATHSTEERING-TLV-TYPE TLV-LENGTH BYTE{8}
```

PathSteering TLV

The second new field represents the HopLimit. The value of this field is decremented when the request is received by each next-hop forwarder. When its value reaches 0, the forwarder has to discard the request. The format of this request is the following:

```
HopLimit TLV ::= HOPLIMIT-TLV-TYPE TLV-LENGTH BYTE{1}
```

HopLimit TLV

Since the NDN packet format does provide a mechanism to prevent the network from caching specific data packets, we will use the MustBeFresh selector for requests (in combination with a Freshness Period TLV of value 0 for replies) to avoid fetching cached traceroute replies.

5.2. Traceroute Reply NDN Packet Format

A traceroute reply is encoded as an NDN Data packet. Its format is the following:

```
TracerouteReply ::= DATA-TLV TLV-LENGTH
                    PathSteering TLV
                    Name
                    MetaInfo
                    Content
                    Signature
```

Traceroute Reply NDN Packet Format

Compared to the format of a regular NDN Data packet, a traceroute reply contains a PathSteering TLV field, which is not included in the security envelope, since it might be modified in a hop-by-hop fashion by the forwarders along the reverse path.

The name of a traceroute reply is the name of the corresponding traceroute request, while the format of the MetaInfo field is the following:

```
MetaInfo ::= META-INFO-TYPE TLV-LENGTH
             ContentType
             FreshnessPeriod
```

MetaInfo TLV

The value of the ContentType TLV is 0. The same applies to the value of the FreshnessPeriod TLV, so that the replies are treated as stale data as soon as they are received by a forwarder.

The content of a traceroute reply consists of the following 2 TLVs: Sender's name (an NDN Name TLV) and Traceroute Reply Code. There is no need to have a separate TLV for the sender's signature in the content of the reply, since every NDN data packet carries the signature of the data producer.

The Traceroute Reply Code TLV format is the following (with the values specified in Section 4.2):

```
TrReplyCode ::= TRREPLYCODE-TLV-TYPE TLV-LENGTH BYTE{2}
```

Traceroute Reply Code TLV

6. Forwarder Handling

When a forwarder receives a traceroute request, the hop limit value will be checked and decremented and the target name (i.e, the name of the traceroute request without the last nonce name component and the suffix "traceroute" in the case of a request with the NDN packet format) will be extracted.

If the HopLimit value is not expired (has not reached 0), the forwarder will forward the request upstream based on CS lookup, PIT creation, LPM lookup and the path steering value, if present. If no valid next-hop is found, an InterestReturn in the case of CCNx and a network NACK in the case of NDN is sent downstream.

If the HopLimit value is equal to zero, the forwarder will generate a traceroute reply. This reply will include the forwarder's own name and signature, and a PathSteering TLV. This TLV initially has a null value since the traceroute reply originator does not forward the request and, thus, does not make a path choice. The reply will also include the appropriate TrReply Code TLV.

A traceroute reply will be the final reply of a traceroute session if one of the following conditions are met:

- Assuming that a forwarder has been given one or more administrative names, the target name matches one of them.
- The target name exactly matches the name of a content-object residing in the forwarder's CS (unless the traceroute client application has chosen not to receive replies due to CS hits as specified in Appendix A).
- The target name matches (in a Longest Prefix Match manner) a FIB entry with an outgoing face referring to a local application.

The TrReply Code TLV value of the reply will indicate the specific condition that was met. If none of those conditions was met, the TrReply Code will be 4 to indicate that the hop limit value reached 0.

A received traceroute reply will be matched to an existing PIT entry as usual. On the reverse path, the path steering TLV of a reply will be updated by each forwarder to encode its choice of next-hop(s). When included in subsequent requests, this path steering TLV will allow the forwarders to steer the requests along the same path.

7. Protocol Operation For Locally-Scoped Namespaces

In this section, we elaborate on 2 alternative design approaches in cases that the traceroute target prefix corresponds to a locally-scoped namespace not directly routable from the client's local network.

The first approach leverages the NDN Link Object [SNAMP]. Specifically, the traceroute client attaches to the expressed request a LINK Object that contains a number of routable name prefixes, based on which the request can be forwarded across the Internet until it reaches a network region, where the request name itself is routable. A LINK Object is created and signed by a data producer allowed to publish data under a locally-scoped namespace. The way that a client retrieves a LINK Object has to do with the overall network architecture design and is out of the scope of the current draft.

Based on the current deployment of the LINK Object by the NDN team, a forwarder at the boarder of the region, where an Interest name becomes routable has to remove the LINK Object from the incoming Interests. The Interest state maintained along the entire forwarding path is based on the Interest name regardless of whether it was forwarded based on this name or a prefix in the LINK Object.

The second approach is based on prepending a routable prefix to the locally-scoped name. The resulting prefix will be the name of the requests expressed by the client. In this way, a request will be forwarded across the Internet based on the routable part of its name. When it reaches the network region, where the original locally-scoped name is routable, the boarder forwarder will have to rewrite the request name and delete its routable part. There are two conditions for a forwarder to perform this rewriting operation on a request: 1) the routable part of the request name matches a routable name of the network region adjacent to the forwarder (assuming that a forwarder is aware of those names) and 2) the remaining part of the request name is routable across the network region of this forwarder.

The state maintained along the path, where the locally-scoped name is not routable, is based on the routable prefix along with the locally-scoped prefix, while within the network region that the locally-scoped prefix is routable is based only on it. To ensure that the generated replies will reach the client, the boarder forwarder has also to rewrite the name of a reply and prepend the routable prefix of the corresponding request.

8. Security Considerations

Reflection attack concerns can arise when a compromised forwarder generates a traceroute reply. In such cases, the compromised forwarder can attach the name of a victim forwarder to the reply payload to redirect future administrative traffic towards the victim. To mitigate these attack scenarios, the forwarder that generates a reply has to sign the name TLV contained in the reply message. When the client receives a traceroute reply, it will be able to verify that the key that signed the name in the reply message can be trusted for both the traceroute prefix and the name of the forwarder that generated the reply. Instead of including a raw name TLV and a signature in the reply message, the forwarder can include its routable prefix(es) encoded as a signed NDN Link Object [SNAMP]. Each forwarder can generate the signature of its own name or its LINK Object in the beginning of its operation instead of doing so during the generation of each individual reply.

This approach does not protect against on-path attacks, where a compromised forwarder that receives a traceroute reply replaces the forwarder’s name and the signature in the message with its own name and signature to make the client believe that the reply was generated by the compromised forwarder. To mitigate such attack scenarios, a forwarder can sign the reply message itself. In such cases, the forwarder does not have to sign its own name in reply message, since the message signature protects the message as a whole and will be invalidated in the case of an on-path attack.

Signing each traceroute reply message can be expensive and can potentially lead to computation attacks against forwarders. To mitigate such attack scenarios, the processing of traceroute requests and the generation of the replies can be handled by a separate management application running locally on each forwarder. Serving traceroute replies is a load on the forwarder. The approaches used by ICN applications to manage load may also apply to the forwarder’s management application.

Interest flooding attack amplification is possible in the case of the second approach to deal with locally-scoped namespaces described in Section 7. A boarder forwarder will have to maintain extra state to

prepend the correct routable prefix to the name of an outgoing reply, since the forwarder might be attached to multiple network regions (reachable under different prefixes) or a network region attached to this forwarder might be reachable under multiple routable prefixes.

We should also note that traceroute requests have the same privacy characteristics as regular Interests.

9. References

9.1. Normative References

[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <http://www.rfc-editor.org/info/rfc2119>.

9.2. Informative References

[CCNMessages] Mosko, M., Solis, I., and C. Wood, "CCNx Messages in TLV Format.", 2016, <https://tools.ietf.org/html/draft-irtf-icnrg-ccnxmessages-03>.

[LIPSIN] Jokela, P. and et al, "LIPSIN: line speed publish/ subscribe inter-networking, ACM SIGCOMM Computer Communication Review 39.4: 195-206", 2009.

[NDNTLV] NDN Project Team, , "NDN Packet Format Specification.", 2016, <http://named-data.net/doc/ndn-tlv/>.

[SNAMP] Afanasyev, A. and et al, "SNAMP: Secure namespace mapping to scale NDN forwarding, IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)", 2015.

Appendix A. Traceroute Client Application (Consumer) Operation

This section is an informative appendix regarding the proposed traceroute client operation.

The client application is responsible for generating traceroute requests for prefixes provided by users.

The overall process can be iterative: The first traceroute request of each session will have a HopLimit of value 1 to reach the first hop forwarder, the second of value 2 to reach the second hop forwarder and so on and so forth.

When generating a series of requests for a specific name, the first one will typically not include a PathSteering TLV, since no TLV value is known. After a traceroute reply containing a PathSteering TLV is received, each subsequent request might include the received path steering value in the PathSteering header TLV to drive the requests towards a common path as part of checking the network performance. To discover more paths, a client can omit the PathSteering TLV in future requests. Moreover, for each new traceroute request, the client has to generate a new nonce and record the time that the request was expressed. It will also set the lifetime of a request, which will have semantics similar to the lifetime of an Interest.

Moreover, the client application might like not to receive replies due to CS hits. In CCNx, a mechanism to achieve that would be to use a Content Object Hash Restriction TLV with a value of 0 in the payload of a traceroute request message. In NDN, the exclude filter selector can be used.

When it receives a traceroute reply, the client would typically match the reply to a sent request and compute the round-trip time of the request. It should parse the PathSteering value and decode the reply's payload to parse the the sender's name and signature. The client should verify that both the received message and the forwarder's name have been signed by the key of the forwarder, whose name is included in the payload of the reply (by fetching this forwarder's public key and verifying the contained signature). In the case that the client receives an TrReply Code TLV with a valid value, it can stop sending requests with increasing HopLimit values and potentially start a new traceroute session.

In the case that a traceroute reply is not received for a request within a certain time interval (lifetime of the request), the client should time-out and send a new request with a new nonce value up to a maximum number of requests to be sent specified by the user.

Appendix B. Open Design Questions

In this section, we describe the open questions of our ICN traceroute protocol design.

The current design can steer subsequent traceroute requests along the same forwarding path (single-path traceroute). It can also opportunistically forward subsequent requests along different paths if the client does not attach a PathSteering TLV to the requests letting the network decide how to forward them. However, one of the objectives of ICN traceroute, as stated in Section 3, is to discover a specific number of available paths and steer requests along them in a deterministic manner (multi-path traceroute). The open question is

how the ICN multi-path traceroute client could keep track of the multiple available paths and iteratively traverse them by using distinct PathSteering TLVs.

In the previous appendix section, we mentioned the mechanism in CCNx and NDN that a traceroute client can use in order to avoid receiving replies due to CS hits (bypass the caches along the path). If, in the future, a specific Interest cache control mechanism to bypass caches is added to the CCNx and NDN protocol specification, this mechanism can be used by the ICN traceroute clients as well.

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