CCNinfo: Discovering Content and Network Information in Content-Centric Networks
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Abstract

This document describes a mechanism named "CCNinfo" that discovers information about the network topology and in-network cache in Content-Centric Networks (CCN). CCNinfo investigates: 1) the CCN routing path information per name prefix, 2) the Round-Trip Time (RTT) between content forwarder and consumer, and 3) the states of in-network cache per name prefix.

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1. Introduction

In Content-Centric Networks (CCN), publishers provide content through the network, and receivers retrieve content by name. In this network architecture, routers forward content requests by means of their Forwarding Information Bases (FIBs), which are populated by name-based routing protocols. CCN also enables receivers to retrieve content from an in-network cache.

In CCN, while consumers do not generally need to know which content forwarder is transmitting the content to them, operators and developers may want to identify the content forwarder and observe the routing path information per name prefix for troubleshooting or investigating the network conditions.

Traceroute [6] is a useful tool for discovering the routing conditions in IP networks as it provides intermediate router addresses along the path between source and destination and the Round-Trip Time (RTT) for the path. However, this IP-based network tool cannot trace the name prefix paths used in CCN. Moreover, such IP-based network tool does not obtain the states of the in-network cache to be discovered.

This document describes the specification of "CCNinfo", an active networking tool for discovering the path and content caching information in CCN. CCNinfo is designed based on the work previously published in [5].
CCNinfo can be implemented with the ccninfo user command and the forwarding function implementation on a content forwarder (e.g., router). The CCNinfo user (e.g., consumer) invokes the ccninfo command (described in Appendix A) with the name prefix of the content. The ccninfo command initiates the "Request" message (described in Section 3.1). The Request message, for example, obtains routing path and cache information. When an appropriate adjacent neighbor router receives the Request message, it retrieves cache information. If the router is not the content forwarder for the request, it inserts its "Report" block (described in Section 3.1.2) into the Request message and forwards the Request message to its upstream neighbor router(s) decided by its FIB. These two message types, Request and Reply messages, are encoded in the CCNx TLV format [1].

In this way, the Request message is forwarded by routers toward the content publisher, and the Report record is inserted by each intermediate router. When the Request message reaches the content forwarder (i.e., a router who can forward the specified cache or content), the content forwarder forms the "Reply" message (described in Section 3.2) and sends it to the downstream neighbor router. The Reply message is forwarded back toward the user in a hop-by-hop manner. This request-reply message flow, walking up the tree from a consumer toward a publisher, is similar to the behavior of the IP multicast traceroute facility [7].

CCNinfo supports multipath forwarding. The Request messages can be forwarded to multiple neighbor routers. When the Request messages forwarded to multiple routers, the different Reply messages will be forwarded from different routers or publisher.
Figure 1: Request messages forwarded by consumer and routers. CCNinfo user and routers (i.e., Router A, B, C) insert their own Report blocks into the Request message and forward the message toward the content forwarder (i.e., caching router and publisher).

Figure 2: Default behavior. Reply messages forwarded by routers. Each router forwards the Reply message along its PIT entry, and finally the CCNinfo user receives a Reply message from Router C, which is the first-hop router for Publisher. Another Reply message from Caching router is discarded at Router B as the corresponding Reply message was already forwarded.
Figure 3: Full discovery request. Reply messages forwarded by publisher and routers. Each router forwards the Reply message along its PIT entry, and finally the CCNinfo user receives two Reply messages: one from the first-hop router and the other from the caching router.

CCNinfo facilitates the tracing of a routing path and provides: 1) the RTT between content forwarder (i.e., caching router or first-hop router) and consumer, 2) the states of in-network cache per name prefix, and 3) the routing path information per name prefix.

In addition, CCNinfo identifies the states of the cache, such as the following metrics for Content Store (CS) in the content forwarder: 1) size of the cached content objects, 2) number of the cached content objects, 3) number of the accesses (i.e., received Interests) per content, and 4) elapsed cache time and remain cache lifetime of content.

Furthermore, CCNinfo implements policy-based information provisioning that enables administrators to "hide" secure or private information, but does not disrupt the forwarding of messages. This policy-based information provisioning reduces the deployment barrier faced by operators in installing and running CCNinfo on their routers.

2. Terminology

In this document, the key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" are to be interpreted as described in RFC 2119 [3], and indicate requirement levels for compliant CCNinfo implementations.

2.1. Definitions

Since CCNinfo requests flow in the opposite direction to the data flow, we refer to "upstream" and "downstream" with respect to data, unless explicitly specified.

Router
It is a router facilitating CCN-based content retrieval in the path between consumer and publisher.

Scheme name
It indicates a URI and protocol. This document only considers "ccn:" as the scheme name.

Prefix name
A prefix name, which is defined in [2], is a name that does not uniquely identify a single content object, but rather a namespace or prefix of an existing content object name.

Exact name
An exact name, which is defined in [2], is one which uniquely identifies the name of a content object.

Node
It is a router, publisher, or consumer.

Content forwarder
It is either a caching router or a first-hop router that forwards content objects to consumers.

CCNinfo user
It is a node that invokes the ccninfo command and initiates the CCNinfo Request.

Incoming face
The face on which data is expected to arrive from the specified name prefix.

Outgoing face
The face to which data from the publisher or router is expected to transmit for the specified name prefix. It is also the face on which the Request messages are received.

Upstream router
The router, connecting to the Incoming face of a router, which is responsible for forwarding data for the specified name prefix to the router.
First-hop router (FHR)
The router that is directly connected to the publisher.

Last-hop router (LHR)
The router that is directly connected to the consumers.

3. CCNinfo Message Formats

CCNinfo uses two message types: Request and Reply. Both messages are encoded in the CCNx TLV format ([1], Figure 4). The Request message consists of a fixed header, Request block TLV Figure 8, and Report block TLV(s) Figure 11. The Reply message consists of a fixed header, Request block TLV, Report block TLV(s), and Reply block/sub-block TLV(s) Figure 14.

```
+---------------+---------------+---------------+---------------+
|    Version    |  PacketType   |         PacketLength          |
+---------------+---------------+---------------+---------------+
|           PacketType specific fields          | HeaderLength  |
+---------------+---------------+---------------+---------------+
/ Optional Hop-by-hop header TLVs            /
+-----------------------------------------------+
/ PacketPayload TLVs                          /
+-----------------------------------------------+
/ Optional CCNx ValidationAlgorithm TLV       /
+-----------------------------------------------+
/ Optional CCNx ValidationPayload TLV (ValidationAlg required) /
+-----------------------------------------------+
```

Figure 4: Packet format [1]

The Request and Reply Type values in the fixed header are PT_REQUEST and PT_REPLY, respectively (Figure 5). These messages are forwarded in a hop-by-hop manner. When the Request message reaches the content forwarder, the content forwarder turns the Request message into a Reply message by changing the Type field value in the fixed header from PT_REQUEST to PT_REPLY and forwards back to the node that has initiated the Request message.
The CCNinfo Request and Reply messages MUST begin with a fixed header with either a Request or Reply type value to specify whether it is a Request message or Reply message. Following a fixed header, there can be a sequence of optional hop-by-hop header TLV(s) for a Request message. In the case of a Request message, it is followed by a sequence of Report blocks, each from a router on the path toward the publisher or caching router.

At the beginning of PacketPayload TLVs, one top-level TLV type, T_DISCOVERY (Figure 6), exists at the outermost level of a CCNx protocol message. This TLV indicates that the Name segment TLV(s) and Reply block TLV(s) would follow in the Request or Reply message.

3.1. Request Message

When a CCNinfo user initiates a discovery request (e.g., by ccninfo command described in Appendix A), a CCNinfo Request message is created and forwarded to its upstream router through the Incoming face(s) determined by its FIB.

The Request message format is as shown in Figure 7. It consists of a fixed header, Request block TLV (Figure 8), Report block TLV(s) (Figure 11), and Name TLV. The Type value of Top-Level type namespace is T_DISCOVERY (Figure 6). The Type value for the Report message is PT_REQUEST.
Figure 7: Request message consists of a fixed header, Request block TLV, Report block TLV(s), and Name TLV

HopLimit: 8 bits

HopLimit is a counter that is decremented with each hop whenever a Request packet is forwarded. It limits the distance a Request may travel on the network.

ReturnCode: 8 bits

ReturnCode is used for the Reply message. This value is replaced by the content forwarder when the Request message is returned as the Reply message (see Section 3.2). Until then, this field MUST be transmitted as zeros and ignored on receipt.
<table>
<thead>
<tr>
<th>Value</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>%x00</td>
<td>NO_ERROR</td>
<td>No error</td>
</tr>
<tr>
<td>%x01</td>
<td>WRONG_IF</td>
<td>CCNinfo Request arrived on an interface to which this router would not forward for the specified name/function toward the publisher.</td>
</tr>
<tr>
<td>%x02</td>
<td>INVALID_REQUEST</td>
<td>Invalid CCNinfo Request is received.</td>
</tr>
<tr>
<td>%x03</td>
<td>NO_ROUTE</td>
<td>This router has no route for the name prefix and no way to determine a potential route.</td>
</tr>
<tr>
<td>%x04</td>
<td>NO_INFO</td>
<td>This router has no cache information for the specified name prefix.</td>
</tr>
<tr>
<td>%x05</td>
<td>NO_SPACE</td>
<td>There was not enough room to insert another Report block in the packet.</td>
</tr>
<tr>
<td>%x06</td>
<td>INFO_HIDDEN</td>
<td>Information is hidden from this discovery because of some policy.</td>
</tr>
<tr>
<td>%x0E</td>
<td>ADMIN_PROHIB</td>
<td>CCNinfo Request is administratively prohibited.</td>
</tr>
<tr>
<td>%x0F</td>
<td>UNKNOWN_REQUEST</td>
<td>This router does not support/recognize the Request message.</td>
</tr>
<tr>
<td>%x80</td>
<td>FATAL_ERROR</td>
<td>A fatal error is one where the router may know the upstream router but cannot forward the message to it.</td>
</tr>
</tbody>
</table>

Reserved (MBZ): 8 bits

The reserved fields in the Value field MUST be transmitted as zeros and ignored on receipt.

3.1.1. Request Block

When a CCNinfo user transmits the Request message, it MUST insert the Request block TLV (Figure 8) and the Report block TLV (Figure 11) of its own to the Request message before sending it through the Incoming face(s).
Figure 8: Request block TLV (hop-by-hop header)

<table>
<thead>
<tr>
<th>Code</th>
<th>Type name</th>
</tr>
</thead>
<tbody>
<tr>
<td>%x0000</td>
<td>Reserved [1]</td>
</tr>
<tr>
<td>%x0001</td>
<td>T_INTLIFE [1]</td>
</tr>
<tr>
<td>%x0002</td>
<td>T_CACHETIME [1]</td>
</tr>
<tr>
<td>%x0003</td>
<td>T_MSGHASH [1]</td>
</tr>
<tr>
<td>%x0004-%x0007</td>
<td>Reserved [1]</td>
</tr>
<tr>
<td>%x0008</td>
<td>T_DISC_REQ</td>
</tr>
<tr>
<td>%x0009</td>
<td>T_DISC_REPORT</td>
</tr>
<tr>
<td>%x0FFE</td>
<td>T_PAD [1]</td>
</tr>
<tr>
<td>%x0FF</td>
<td>T_ORG [1]</td>
</tr>
<tr>
<td>%x1000-%x1FFF</td>
<td>Reserved [1]</td>
</tr>
</tbody>
</table>

Figure 9: Hop-by-Hop Type Namespace

Type: 16 bits

Format of the Value field. For the single Request block TLV, the type value MUST be T_DISC_REQ. For all the available types for hop-by-hop type namespace, please see Figure 9.

Length: 16 bits

Length of Value field in octets.

Request ID: 16 bits

This field is used as a unique identifier for this CCNinfo Request so that duplicate or delayed Reply messages can be detected.

SkipHopCount: 8 bits
Number of skipped routers for a Request. This value MUST be lower than the value of HopLimit at the fixed header.

Flags: 16 bits

Flags field is used to indicate the types of the content or path discoveries. Currently, as shown in Figure 10, three bits, "C", "O", and "F", are assigned, and the other 5 bits are reserved (MBZ) for the future use. These flags are set by CCNinfo users when they initiate Requests (see Appendix A), and routers that receive the Requests deal with the flags and change the behaviors (see Section 5 for details).

<table>
<thead>
<tr>
<th>Flag</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>Path discovery (i.e., no cache information retrieved)</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>Cache information retrieval (default)</td>
</tr>
<tr>
<td>O</td>
<td>0</td>
<td>Request to any content forwarder (default)</td>
</tr>
<tr>
<td>O</td>
<td>1</td>
<td>Publisher reachability (i.e., only FHR can reply)</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>Request based on FIB’s strategy (default)</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>Full discovery request. Request to multiple upstream routers simultaneously</td>
</tr>
</tbody>
</table>

Figure 10: Codes and types specified in Flags field

3.1.2. Report Block

A CCNinfo user and each upstream router along the path would insert its own Report block TLV without changing the Type field of the fixed header of the Request message until one of these routers is ready to send a Reply. In the Report block TLV (Figure 11), the Request Arrival Time and the Node Identifier MUST be inserted.

```
1                   2                   3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+---------------+---------------+---------------+---------------+
|         T_DISC_REPORT         |             Length            |
+---------------+---------------+---------------+---------------+
|                     Request Arrival Time                      |
+---------------+---------------+---------------+---------------+
/                        Node Identifier                        /
+---------------+---------------+---------------+---------------+
```

Figure 11: Report block TLV (hop-by-hop header)

Type: 16 bits
Format of the Value field. For the Report block TLV, the type value(s) MUST be T_DISC_REPORT in the current specification.

Length: 16 bits

Length of Value field in octets.

Request Arrival Time: 32 bits

The Request Arrival Time is a 32-bit NTP timestamp specifying the arrival time of the CCNinfo Request packet at this router. The 32-bit form of an NTP timestamp consists of the middle 32 bits of the full 64-bit form; that is, the low 16 bits of the integer part and the high 16 bits of the fractional part.

The following formula converts from a UNIX timeval to a 32-bit NTP timestamp:

\[
\text{request\_arrival\_time} = ((\text{tv.tv\_sec} + 32384) \ll 16) + ((\text{tv.tv\_nsec} \ll 7) / 1953125)
\]

The constant 32384 is the number of seconds from Jan 1, 1900 to Jan 1, 1970 truncated to 16 bits. \((\text{tv.tv\_nsec} \ll 7) / 1953125\) is a reduction of \((\text{tv.tv\_nsec} / 1000000000) \ll 16\).

Note that it is RECOMMENDED that all the routers on the path to have synchronized clocks; however, if they do not have synchronized clocks, CCNinfo measures one-way latency.

Node Identifier: variable length

This field specifies the CCNinfo user or the router identifier (e.g., IPv4 address) of the Incoming face on which packets from the publisher are expected to arrive, or all-zeros if unknown or unnumbered. Since we may not always rely on the IP addressing architecture, it would be necessary to define the identifier uniqueness (e.g., by specifying the protocol family) for this field. However, defining such uniqueness is out of scope of this document. Potentially, this field may be defined as a new TLV based on the CCNx TLV format [1].

3.2. Reply Message

When a content forwarder receives a CCNinfo Request message from the appropriate adjacent neighbor router, it would insert a Reply block TLV and Reply sub-block TLV(s) of its own to the Request message and turn the Request into the Reply by changing the Type field of the fixed header of the Request message from PT_REQUEST to PT_REPLY. The
Reply message (see Figure 12) would then be forwarded back toward the CCNinfo user in a hop-by-hop manner.

![Figure 12: Reply message consists of a fixed header, Request block TLV, Report block TLV(s), Name TLV, and Reply block/sub-block TLV(s)](image-url)
3.2.1. Reply Block

The Reply block TLV is an envelope for Reply sub-block TLV(s) (explained in Section 3.2.1.1).

```
1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+---------------+---------------+---------------+
|         T_DISC_REPLY          |             Length            |
+---------------+---------------+---------------+
```

Figure 14: Reply block TLV (packet payload)

Type: 16 bits

Format of the Value field. For the Reply block TLV, the type value MUST be T_DISC_REPLY in the current specification.

Length: 16 bits

Length of Value field in octets. This length is a total length of Reply sub-block(s).

3.2.1.1. Reply Sub-Block

In addition to the Reply block, a router on the traced path will add one or multiple Reply sub-blocks followed by the Reply block before sending the Reply to its neighbor router.

The Reply sub-block is flexible for various purposes. For instance, operators and developers may want to obtain various characteristics of content such as content’s ownership and copyright, or other cache...
states and conditions. In this document, Reply sub-block TLVs for T_DISC_CONTENT and T_DISC_CONTENT_OWNER (Figure 15) are defined; other Reply sub-block TLVs will be defined in separate document(s).

![Figure 15: Reply sub-block TLV for T_DISC_CONTENT and T_DISC_CONTENT_OWNER (packet payload)](image_url)

<table>
<thead>
<tr>
<th>Code</th>
<th>Type name</th>
</tr>
</thead>
<tbody>
<tr>
<td>%x0000</td>
<td>T_DISC_CONTENT</td>
</tr>
<tr>
<td>%x0001</td>
<td>T_DISC_CONTENT_OWNER</td>
</tr>
<tr>
<td>%x0FFF</td>
<td>T_ORG</td>
</tr>
<tr>
<td>%x1000-%x1FFF</td>
<td>Reserved (Experimental Use)</td>
</tr>
</tbody>
</table>

![Figure 16: CCNinfo Reply Type Namespace](image_url)

Type: 16 bits

Format of the Value field. For the Reply sub-block TLV, the type value MUST be one of the type value defined in the CCNinfo Reply Type Namespace (Figure 16). T_DISC_CONTENT is specified when the cache information is replied from a caching router. T_DISC_CONTENT_OWNER is specified when the content information is replied from a FHR attached to a publisher.

Length: 16 bits

Length of Value field in octets.

Object Size: 32 bits

The total size (byte) of the (cached) content objects. Note that the maximum size expressed by 32 bit field is about 4.29 GB. This value MAY be null when FHR sends the Reply message.

Object Count: 32 bits

The number of the (cached) content objects. Note that the maximum count expressed by 32 bit field is about 4.29 billion. This value MAY be null when FHR sends the Reply message.

# Received Interest: 32 bits

The total number of the received Interest messages to retrieve the cached content objects.

First Seqnum: 32 bits

The first sequential number of the (cached) content objects. This value MAY be null if the router does not know or cannot report.

Last Seqnum: 32 bits

The last sequential number of the (cached) content objects. Above First Seqnum and this Last Seqnum do not guarantee the consecutiveness of the cached content objects. This value MAY be null if the router does not know or cannot report.

Elapsed Cache Time: 32 bits

The elapsed time (seconds) after the oldest content object of the content is cached. This value MAY be null if the router does not know or cannot report.

Remain Cache Lifetime: 32 bits

The lifetime (seconds) of a content object, which is removed first among the cached content objects. This value MAY be null if the router does not know or cannot report.

Specification of the Name TLV (whose type value is T_NAME) and the Name Segment TLVs are described in [1], and CCNinfo follows that specification. CCNinfo also allows to specify the content name
either with a prefix name (such as "ccn:/news/today") or an exact name (such as "ccn:/news/today/Chunk=10"). When a CCNinfo user specifies a prefix name, s/he will obtain the information of the matched content objects in the content forwarder. On the other hand, when a CCNinfo user specifies an exact name, s/he will obtain only about the specified content object in the content forwarder.

4. CCNinfo User Behavior

4.1. Sending CCNinfo Request

The CCNinfo user’s program (e.g., ccninfo command) enables user to obtain both the routing path information and in-network cache information in a same time.

A CCNinfo user initiates a CCNinfo Request by sending the Request message to the adjacent neighbor router(s) of interest. As a typical example, a CCNinfo user invokes the ccninfo command (detailed in Appendix A) that forms a Request message and sends it to the user’s adjacent neighbor router(s).

When the CCNinfo user’s program initiates a Request message, it MUST insert the necessary values, the "Request ID" (in the Request block) and the "Node Identifier" (in the Report block), in the Request and Report blocks. The Request ID MUST be unique for the CCNinfo user until s/he receives the corresponding Reply message(s) or times out the Request.

Because of some policy, a router needs to validate CCNinfo Requests (whether it accepts the Request or not) especially when the router receives the "full discovery request" (see Section 5.3). To support this requirement, the CCNinfo user’s program MAY require appending the user’s signature into the CCNx ValidationPayload TLV. The router then forwards the Request message or reply the Reply message whenever it approves the Request.

After the CCNinfo user’s program sends the Request message, until the Reply times out or the expected numbers of Replies or a Reply message having a non-zero ReturnCode in the fixed header is received, the CCNinfo user’s program MUST keep the following information; Request ID and Flags specified in the Request block, Node Identifier and Request Arrival Time specified in the Report block, and HopLimit specified in the fixed header.
4.1.1. Routing Path Information

A CCNinfo user can send a CCNinfo Request for investigating routing
path information for the specified named content. By the Request,
the legitimate user can obtain; 1) identifiers (e.g., IP addresses)
of intermediate routers, 2) identifier of content forwarder, 3)
number of hops between content forwarder and consumer, and 4) RTT
between content forwarder and consumer, per name prefix. This
CCNinfo Request is terminated when it reaches the content forwarder.

4.1.2. In-Network Cache Information

A CCNinfo user can send a CCNinfo Request for investigating in-
network cache information. By the Request, the legitimate user can
obtain; 1) size of the cached content objects, 2) number of the
cached content objects, 3) number of the accesses (i.e., received
Interests) per content, and 4) lifetime and expiration time of the
cached content object, for Content Store (CS) in the content
forwarder. This CCNinfo Request is terminated when it reaches the
content forwarder.

4.2. Receiving CCNinfo Reply

A CCNinfo user’s program will receive one or multiple CCNinfo Reply
messages from the adjacent neighbor router that has previously
received and forwarded the Request message(s). When the program
receives the Reply, it MUST compare the kept Request ID and Node
Identifier and the ones noted in the Request block TLV in the Reply.
If they do not match, the Reply message MUST be silently discarded.

If the number of the Report blocks in the received Reply is more than
the initial HopLimit value (which was inserted in the original
Request), the Reply MUST be silently ignored.

After the CCNinfo user has determined that s/he has traced the whole
path or as much as s/he can expect to, s/he might collect statistics
by waiting a timeout. Useful statistics provided by CCNinfo can be
seen in Section 8.

5. Router Behavior

5.1. User and Neighbor Verification

Upon receiving a CCNinfo Request message, a router MAY examine
whether the message comes from a valid CCNinfo user. If the router
recognizes that the Request sender’s signature specified in the
Request is invalid, it terminates the Request as defined in
Section 6.3.
Upon receiving a CCNinfo Request/Reply message, a router MAY examine whether the message comes from a valid adjacent neighbor node. If the router recognizes that the Request/Reply sender is invalid, the Request/Reply message MUST be silently ignored. See Section 9.8.

5.2. Receiving CCNinfo Request

5.2.1. Normal Processing

After the CCNinfo Request message verification, the router performs the following steps.

1. The value of the "HopLimit" in the fixed header and the value of the "SkipHopCount" in the Request block are counters that are decremented with each hop. If the HopLimit value is zero, the router terminates the Request as defined in Section 6.4. If the SkipHopCount value is equal or more than the HopLimit value, the router terminates the Request as defined in Section 6.3. Otherwise, until the SkipHopCount value becomes zero, the router forwards the Request message to the upstream router(s) without adding its own Report block and without replying the Request. If the router does not know the upstream router(s) for the specified name prefix, it terminates the Request as defined in Section 6.4.

2. The router examines the Flags field (specified in Figure 10) in the Request block of received CCNinfo Request. If the "C" flag is set but the "O" flag is not set, that is categorized as the "cache information discovery". If both the "C" and "O" flags are not set, that is categorized as the "routing path information discovery". If "O" flag is set, that is categorized as the "publisher discovery".

3. If the Request is either the "cache information discovery" or the "routing path information discovery", the router examines its FIB and CS. If the router caches the specified content, it inserts own Report block in the hop-by-hop header, and sends the Reply message with own Reply block and sub-block(s) (in case of cache information discovery) or sends the Reply message with own Reply block without adding any Reply sub-block (in case of routing path information discovery). If the router does not cache the specified content but knows the upstream neighbor router(s) for the specified name prefix, it inserts own Report block and forwards the Request to the upstream neighbor(s). If the router does not cache the specified content and does not know the upstream neighbor router(s) for the specified name prefix, it terminates the Request as defined in Section 6.4.
4. If the Request is the "publisher discovery", the router examines whether it is the FHR for the requested content. If it is the FHR, it sends the Reply message with own Report block and sub-block. If the router is not the FHR but knows the upstream neighbor router(s) for the specified name prefix, it adds the own Report block and forwards the Request to the neighbor(s). If the node is not the FHR and does not know the upstream neighbor router(s) for the specified name prefix, it terminates the Request as defined in Section 6.4.

5.3. Forwarding CCNinfo Request

When a router decides to forward a Request message with its Report block to its upstream router(s), it specifies the Request Arrival Time and Node Identifier in the Report block of the Request message. The router then forwards the Request message upstream toward the publisher or caching router based on the FIB entry.

When the router forwards the Request message, it MUST record the Request ID, the F flag, and the Node Identifier specified in the Request block at the corresponding PIT entry. The router can later check the PIT entry to correctly forward back the Reply message(s). (See below.)

CCNinfo supports multipath forwarding. The Request messages can be forwarded to multiple neighbor routers. Some router may have strategy for multipath forwarding; when it sends Interest messages to multiple neighbor routers, it may delay or prioritize to send the message to the upstream routers. The CCNinfo Request, as the default, complies with such strategy; a CCNinfo user could trace the actual forwarding path based on the forwarding strategy.

On the other hand, there may be the case that a CCNinfo user wants to discover all potential forwarding paths based on routers’ FIBs. The "full discovery request" enables this function. If a CCNinfo user sets the F flag in the Request block of the Request message (as seen in Figure 10) to request the full discovery, the upstream routers forward the Requests to the all multiple upstream routers based on the FIBs simultaneously. Then the CCNinfo user could trace the all potential forwarding paths. Note that some routers MAY ignore the full discovery request according to their policy. In that case, the router terminates the Request as defined in Section 6.10.

When the Request messages forwarded to multiple routers, the different Reply messages will be forwarded from different routers or publisher. To support this case, PIT entries initiated by CCNinfo remain until the configured CCNinfo Reply Timeout (Section 7.1) passes. In other words, unlike the ordinary Interest-Data
communications in CCN, the router SHOULD NOT remove the PIT entry created by the CCNinfo Request until the timeout value expires.

CCNinfo Requests SHOULD NOT result in PIT aggregation in routers during the Request message transmission.

5.4. Sending CCNinfo Reply

When a router decides to send a Reply message to its downstream neighbor router or the CCNinfo user with NO_ERROR return code, it inserts a Report block having the Request Arrival Time and Node Identifier to the hop-by-hop TLV header of the Request message. And then the router inserts the corresponding Reply block with an appropriate type value (Figure 15) and Reply sub-block(s) to the payload. The router does not insert any Reply block/sub-block if there is an error. The router finally changes the Type field in the fixed header from PT_REQUEST to PT_REPLY and forwards the message back as the Reply toward the CCNinfo user in a hop-by-hop manner.

If a router cannot continue the Request, it MUST put an appropriate ReturnCode in the Request message, change the Type field value in the fixed header from PT_REQUEST to PT_REPLY, and forward the Reply message back toward the CCNinfo user, to terminate the request. See Section 6.

5.5. Forwarding CCNinfo Reply

When a router receives a CCNinfo Reply whose Request ID and Node Identifier match the ones in the PIT entry and sent from a valid adjacent neighbor router, it forwards the CCNinfo Reply back toward the CCNinfo user. If the router does not receive the corresponding Reply within the [CCNinfo Reply Timeout] period, then it removes the corresponding PIT entry and terminates the trace.

Flags field in the Request block TLV is used to indicate whether the router keeps the PIT entry during the CCNinfo Reply Timeout even after one or more corresponding Reply messages are forwarded. When the CCNinfo user does not set the F flag (i.e., "0"), the intermediate routers immediately remove the PIT entry whenever they forward the corresponding Reply message. When the CCNinfo user sets the F flag (i.e., "1"), which means the CCNinfo user chooses the "full discovery request", the intermediate routers keep the PIT entry within the [CCNinfo Reply Timeout] period. After this timeout, the PIT entry is removed.

CCNinfo Replies MUST NOT be cached in routers upon the Reply message transmission.
6. CCNinfo Termination

When performing an expanding hop-by-hop trace, it is necessary to determine when to stop expanding. There are several cases an intermediate router might return a Reply before a Request reaches the caching router or the publisher.

6.1. Arriving at First-hop router

A CCNinfo Request can be determined to have arrived at the first-hop router.

6.2. Arriving at Router Having Cache

A CCNinfo Request can be determined to have arrived at the router having the specified content cache within the specified HopLimit.

6.3. Invalid Request

If the router does not accept the Request, the router MUST note a ReturnCode of INVALID_REQUEST in the fixed header of the message and forward the message without appending any Reply (sub-)block TLV as the Reply back to the CCNinfo user. The router MAY, however, randomly ignore the received invalid messages. (See Section 9.6.)

6.4. No Route

If the router cannot determine the routing paths or neighbor routers for the specified name prefix within the specified HopLimit, the router MUST note a ReturnCode of NO_ROUTE in the fixed header of the message and forward the message as the Reply back to the CCNinfo user.

6.5. No Information

If the router does not have any information about the specified name prefix within the specified HopLimit, the router MUST note a ReturnCode of NO_INFO in the fixed header of the message and forward the message as the Reply back to the CCNinfo user.

6.6. No Space

If appending the Report block would exceed the maximum (i.e., 255 byte) header length or make the CCNinfo Request message longer than the MTU of the Incoming face or longer than 1280 bytes (especially in the situation supporting IPv6 as the payload [4]), the router MUST note a ReturnCode of NO_SPACE in the fixed header of the message and forward the message as the Reply back to the CCNinfo user.
6.7. Fatal Error

A CCNinfo Request has encountered a fatal error if the last 
ReturnCode in the trace has the 0x80 bit set (see Section 3.1).

6.8. CCNinfo Reply Timeout

If a router receives the Request or Reply message that expires its 
own [CCNinfo Reply Timeout] value (Section 7.1), the router will 
silently discard the Request or Reply message.

6.9. Non-Supported Node

Cases will arise in which a router or a publisher along the path does 
not support CCNinfo. In such cases, a CCNinfo user and routers that 
forward the CCNinfo Request will time out the CCNinfo request.

6.10. Administratively Prohibited

If CCNinfo is administratively prohibited, the router rejects the 
Request message and MUST reply the CCNinfo Reply with the ReturnCode 
of ADMIN_PROHIB. The router MAY, however, randomly ignore the 
rejected messages. (See Section 9.6.)

7. Configurations

7.1. CCNinfo Reply Timeout

The [CCNinfo Reply Timeout] value is used to time out a CCNinfo 
Reply. The value for a router can be statically configured by the 
router's administrators/operators. The default value is 4 (seconds).  
The [CCNinfo Reply Timeout] value SHOULD NOT be larger than 5 
(seconds) and SHOULD NOT be lower than 2 (seconds).

7.2. HopLimit in Fixed Header

If a CCNinfo user does not specify the HopLimit value in a fixed 
header for a Request message as the HopLimit, the HopLimit is set to 
32. Note that 0 HopLimit is an invalid Request; hence the router in 
this case follows the way defined in Section 6.3.

7.3. Access Control

A router MAY configure the valid or invalid networks to enable an 
access control. The access control can be defined per name prefix, 
such as "who can retrieve which name prefix". See Section 9.2.
8. Diagnosis and Analysis

8.1. Number of Hops

A CCNinfo Request message is forwarded in a hop-by-hop manner and each forwarding router appended its own Report block. We can then verify the number of hops to reach the content forwarder or the publisher.

8.2. Caching Router Identification

It is possible to identify the routers in the path from the CCNinfo user to the content forwarder, while some routers may hide their identifier (e.g., IP address) with all-zeros in the Report blocks (Section 9.1).

8.3. TTL or Hop Limit

By taking the HopLimit from the content forwarder and forwarding TTL threshold over all hops, it is possible to discover the TTL or hop limit required for the content forwarder to reach the CCNinfo user.

8.4. Time Delay

If the routers have synchronized clocks, it is possible to estimate propagation and queuing delay from the differences between the timestamps at successive hops. However, this delay includes control processing overhead, so is not necessarily indicative of the delay that data traffic would experience.

8.5. Path Stretch

By getting the path stretch "d / P", where "d" is the hop count of the data and "P" is the hop count from the consumer to the publisher, we can measure the improvement in path stretch in various cases, such as different caching and routing algorithms. We can then facilitate investigation of the performance of the protocol.

8.6. Cache Hit Probability

CCNinfo can show the number of received interests per cache or chunk on a router. By this, CCNinfo measures the content popularity (i.e., the number of accesses for each content/cache), and you can investigate the routing/caching strategy in networks.
9. Security Considerations

This section addresses some of the security considerations.

9.1. Policy-Based Information Provisioning for Request

Although CCNinfo gives excellent troubleshooting cues, some network administrators or operators may not want to disclose everything about their network to the public, or may wish to securely transmit private information to specific members of their networks. CCNinfo provides policy-based information provisioning allowing network administrators to specify their response policy for each router.

The access policy regarding "who is allowed to retrieve" and/or "what kind of information" can be defined for each router. For the former access policy, routers having the specified content MAY examine the signature enclosed in the Request message and decide whether they should notify the content information in the Reply or not. If the routers decide to not notify the content information, they MUST reply the CCNinfo Reply with the ReturnCode of ADMIN_PROHIB without appending any Reply (sub-)block TLV. For the latter policy, the permission, whether (1) All (all cache information is disclosed), (2) Partial (cache information with the particular name prefix can (or cannot) be disclosed), or (3) Deny (no cache information is disclosed), is defined at routers.

On the other hand, we entail that each router does not disrupt forwarding CCNinfo Request and Reply messages. When a Request message is received, the router SHOULD insert Report block if the ReturnCode is NO_ERROR. Here, according to the policy configuration, the Node Identifier field in the Report block MAY be null (i.e., all-zeros), but the Request Arrival Time field SHOULD NOT be null. At last, the router SHOULD forward the Request message to the upstream router toward the content forwarder if the ReturnCode is kept with NO_ERROR.

9.2. Filtering of CCNinfo Users Located in Invalid Networks

A router MAY support an access control mechanism to filter out Requests from invalid CCNinfo users. For it, invalid networks (or domains) could, for example, be configured via a list of allowed/disallowed networks (as seen in Section 7.3). If a Request is received from the disallowed network (according to the Node Identifier in the Request block), the Request MUST NOT be processed and the Reply with the ReturnCode of INFO_HIDDEN may be used to note that. The router MAY, however, perform rate-limited logging of such events.
9.3. Topology Discovery

CCNinfo can be used to discover actively-used topologies. If a network topology is a secret, CCNinfo Requests SHOULD be restricted at the border of the domain, using the ADMIN_PROHIB return code.

9.4. Characteristics of Content

CCNinfo can be used to discover what publishers are sending to what kinds of contents. If this information is a secret, CCNinfo Requests SHOULD be restricted at the border of the domain, using the ADMIN_PROHIB return code.

9.5. Longer or Shorter CCNinfo Reply Timeout

Routers can configure the CCNinfo Reply Timeout (Section 7.1), which is the allowable timeout value to keep the PIT entry. If routers configure the longer timeout value, there may be an attractive attack vector against PIT memory. Moreover, especially when the full discovery request option (Section 5.3) is specified for the CCNinfo Request, a number of Reply messages may come back and cause a response storm. (See Section 9.7 for rate limiting to avoid the storm). In order to avoid DoS attacks, routers may configure the timeout value, which is shorter than the user-configured CCNinfo timeout value. However, if it is too short, the Request may be timed out and the CCNinfo user does not receive the all Replies and only retrieves the partial path information (i.e., information about part of the tree).

There may be the way to allow for incremental exploration (i.e., to explore the part of the tree the previous operation did not explore), whereas discussing such mechanism is out of scope of this document.

9.6. Limiting Request Rates

A router may limit CCNinfo Requests by ignoring some of the consecutive messages. The router MAY randomly ignore the received messages to minimize the processing overhead, i.e., to keep fairness in processing requests, or prevent traffic amplification. No error is returned. The rate limit is left to the router’s implementation.

9.7. Limiting Reply Rates

CCNinfo supporting multipath forwarding may result in one Request returning multiple Reply messages. In order to prevent abuse, the routers in the traced path MAY need to rate-limit the Replies. No error is returned. The rate limit function is left to the router’s implementation.
9.8. Adjacency Verification

It is assumed that CCNinfo Request and Reply messages are forwarded by adjacent neighbor nodes or routers. Defining the secure way to verify the adjacency cannot rely on the way specified in CCNx message format or semantics, yet specifying the mechanism to validate adjacent neighbor routers is out of scope of this document. An adjacency verification mechanism and the corresponding TLV for adjacency verification using hop-by-hop TLV header such as [8] is the potential way and will be defined in a separate document.

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11. References

11.1. Normative References


11.2. Informative References


Appendix A.  ccninfo Command and Options

The ccninfo command enables the CCNinfo user to investigate the routing path based on the name prefix of the content (e.g., ccn:/news/today). The name prefix is mandatory but exclusive options; that is, only one of them should be used with the ccninfo command at once.

The usage of ccninfo command is as follows:


name_prefix
Prefix name of content (e.g., ccn:/news/today) or exact name of content (e.g., ccn:/news/today/Chunk=10) the CCNinfo user wants to trace.

f option
This option enables "full discovery request"; routers ignore the forwarding strategy and send CCNinfo Requests to multiple upstream routers simultaneously. The CCNinfo user could then trace the all potential forwarding paths.

n option
This option can be specified if a CCNinfo user only needs the routing path information to the specified content/cache and RTT between CCNinfo user and content forwarder; therefore, cache information is not given.

o option
This option enables to trace the path to the content publisher. Each router along the path to the publisher inserts each Report block and forwards the Request message. It does not send Reply even if it caches the specified content. FHR that attaches the publisher (who has the complete set of content and is not a caching router) replies the Reply message.

r option
Number of traced routers. If the CCNinfo user specifies this option, only the specified number of hops from the CCNinfo user trace the Request; each router inserts its own Report block and forwards the Request message to the upstream router(s), and the
last router stops the trace and sends the Reply message back to the CCNinfo user. This value is set in the "HopLimit" field located in the fixed header of the Request. For example, when the CCNinfo user invokes the CCNinfo command with this option such as "-r 3", only three routers along the path examine their path and cache information. If there is a caching router or FHR within the hop count along the path, the caching router or FHR sends back the Reply message and terminates the trace request. If the last router does not have the corresponding cache, it replies the Reply message with NO_INFO return code (described in Section 3.1) with no Reply block TLV inserted. The Request messages are terminated at FHR; therefore, although the maximum value for this option a CCNinfo user can specify is 255, the Request messages should be in general reached at FHR within significantly lower than 255 hops.

s option

Number of skipped routers. If the CCNinfo user specifies this option, the number of hops from the CCNinfo user simply forward the CCNinfo Request messages without adding its own Report block and without replying the Request, and the next upstream router starts the trace. This value is set in the "SkipHopCount" field located in the Request block TLV. For example, when the CCNinfo user invokes the CCNinfo command with this option such as "-s 3", the three upstream routers along the path only forwards the Request message, but does not append their Report blocks in the hop-by-hop headers and does not send the Reply messages even though they have the corresponding cache. The Request messages are terminated at FHR; therefore, although the maximum value for this option a CCNinfo user can specify is 255, if the Request messages reaches FHR, the FHR silently discards the Request message and the request will be timed out.

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Design Considerations for Applying ICN to IoT

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Abstract

The Internet of Things (IoT) promises to connect billions of objects to the Internet. After deploying many stand-alone IoT systems in different domains, the current trend is to develop a common, "thin waist" of protocols to enable a horizontally unified IoT architecture. The objective of such an architecture is to make resource objects securely accessible to applications across organizations and domains. Towards this goal, quite a few proposals have been made to build an application-layer based unified IoT platform on top of today’s host-centric Internet. However, there is a fundamental mismatch between the host-centric nature of today’s Internet and the mostly information-centric nature of the IoT domain. To address this mismatch, the common set of protocols and network services offered by an information-centric networking (ICN) architecture can be leveraged to realize an ICN-based IoT (or ICN-IoT) architecture that can take advantage of the salient features of ICN such as naming, security, mobility, compute and efficient content and service delivery support offered by it.

In this draft, we summarize the general IoT demands, and ICN features that support these requirements, and then discuss the challenges to realize an ICN-based IoT framework. Beyond this, the goal of this draft is not to offer any specific ICN-IoT architectural proposal.
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1. Introduction

During the past decade, many Internet of Things (IoT) systems have been developed, and deployed in different domains. The recent trend, however, is to evolve these systems towards a unified IoT architecture, in which a large number of objects hosted by non-interoperable protocol domains can connect to the Internet to enable secure interactions with a diverse set of applications across administrative domain. Note that, here, ‘unified’ is used to imply a scenario, where all the IoT applications, services, and network functions use a common set of transport APIs and network protocols to interact with each other. Typical IoT applications involve sensing, actuation, processing, and secure content distribution, each of which can occur at different timescales and hierarchical levels that depend on the application requirements. To adapt to different scenarios, IoT systems need to adopt an architecture that can provide (i) pull/push- and publish/subscribe-based application abstractions, (ii) a common naming framework, (iii) support for payload encryption and signature schemes, and (iv) open APIs as opposed to proprietary APIs.
that are common in today’s systems. These requirements can pose great challenges for the underlying network and systems. To name a few, the IoT system needs to support 50-100 Billion networked objects [1], many of which are mobile. These objects are expected to have extremely heterogeneous means of connecting to the Internet, often with severe resource constraints. Interactions between the applications and the objects are often real-time and dynamic, requiring strong security and privacy protections. In addition, the IoT system design should offer efficient data exchange schemes that take into consideration the application behavior. For instance, in many IoT applications, data consumers usually need the data sensed from the environment without any reference to the subset of sensors that can provide the requested information.

In short, adopting a general IoT perspective, we first motivate the discussion of ICN for IoT by focusing on well known scenarios. We then discuss the IoT requirements that are generally applicable to many of these well known IoT scenarios. Next we discuss how the current application-layer unified IoT architectures are inefficient to meet the above requirements, and how the key ICN features can make it a better candidate to realize a unified IoT framework. Finally, adopting an ICN perspective, we address the main IoT design challenges and requirements posed towards an ICN-based-IoT system design.

2. Motivating ICN for IoT

ICN offers many features that include name-based networking, content object security, in-network caching, compute, and storage, active mobility support, context-aware networking (see Section 3.6), and support for ad hoc networking. Within the context of an IP based IoT design (IP-IoT), all of these features offered by the ICN have to be realized in an application-specific way demonstrating the compelling nature of ICN to design IoT systems.

To be specific, the features offered by ICN can be used to enable a distributed and intelligent data distribution platform that supports heterogeneous IoT services requiring minimal configuration for device bootstrapping, carrying simpler protocols to aid self-organizing among the IoT elements, and offering natural support for compute and caching logic at strategic points in the network. We outline general advantages of using an ICN-based IoT system design and discuss these from the perspective of the several service scenarios that are difficult to realize over IP today, and whose characteristics arguably match the features offered by ICN.
2.1. Advantages of using ICN for IoT

A key concept of ICN is the ability to name data and services independently from its original location (at which it is stored) and this simplifies caching, and enables decoupling of consumers and producers. Therefore, using ICN to design an architecture for IoT data potentially provides many such advantages compared to using traditional host-centric networks and other new architectures. This section highlights the general benefits that the ICN can provide to an IoT network.

- **Naming of Devices, Data and Services:** The heterogeneity of the deployed network equipment and offered services by an IoT network leads to a large variety of data, services, and devices. While using a traditional host-centric architecture, only devices or their network interfaces are named at the network level, leaving the task to name data and services to the application layer. This can cause different applications to use different naming schemes, and, as a result, no consistent mapping from application layer names to network names may exist. In many applications common to an IoT network, data and services represent the main objective, and ICN provides an intuitive way to name them in a way that can be utilized at the network layer as well. Communication with a specific device is often secondary, but when needed, the same ICN naming mechanisms can also be used. In such case, network distributes content and provides a service at the same time, instead of only sending data between two named devices. In this context, content and services can be provided by several devices, or a group of devices, hence naming data and services is often more important than naming the devices. This naming mechanism also enables self-configuration of the IoT system.

- **Security and privacy:** ICN advocates the object security model to secure data in the network. This concept is based on the idea of securing information objects, unlike the session-based security mechanisms, which secure the communication channel between a pair of nodes. ICN provides data integrity through name-data integrity, i.e., the guarantee that the given data corresponds to the name with which it was addressed. Signature-based schemes can additionally provide data authenticity, meaning establishing the origin, or provenance, of the data, for example, by cryptographically linking a data object to the identity of a publisher. Confidentiality can be handled on a per-object basis based on the keys established at the application level. All of this means that the actual transmission of data does not have to be secured, since the same security mechanisms protect the data starting with its generation until its consumption, regardless of its mobility/location (i.e., whether it is in transit over a
communication channel or stored in an intermediate cache). In an ICN network, each individual object within a stream of immutable objects can potentially be retrieved from a cache in a different location. However, having a trust relationship with each of these different caches is not realistic. Through name-data integrity, ICN automatically guarantees data integrity to the requesting client regardless of the location, from where it is delivered. The object security model also ensures that the content is readily available in a secure state, and if the device constraints are severe enough that it is not able to perform the required cryptographic operations for object security, then it may be possible to offload this operation to a trusted gateway, to which only a single secure channel needs to be established. ICN can also derive a name from a public key, as the cryptographic hash of a public key also enables it to be self-certifying, in which case, authenticating the resource object does not require an external authority [27][28].

- Distributed Caching and Processing: While caching mechanisms are already used by other types of overlay networks, IoT networks can potentially benefit even more from caching and in-network processing, because of the resource constraints imposed on the devices. Furthermore, wireless bandwidth and power supply can be limited for multiple devices sharing a communication channel, and especially for small mobile devices powered by batteries. In this case, avoiding unnecessary transmissions to retrieve and distribute IoT data from/to multiple places becomes important, hence processing and storing such content in the network can save wireless bandwidth and battery power. Moreover, as for other types of networks, IoT-driven applications requiring shorter delays can also benefit from local caches and services to reduce the delays between content request and delivery.

- Sender/Receiver Decoupling: IoT devices may be mobile and face intermittent network connectivity issues. When a specific data is requested, such data can often be delivered by ICN without any consistent direct connectivity between devices. Apart from using structured caching systems as described previously, information can also be spread by forwarding data opportunistically.

2.2. Service Scenarios

- Smart Mobility: Smart end-user devices and machine-to-machine (M2M) connections are undergoing a significant growth. By 2021, there will be more than 10 billion mobile devices and connections, including smartphones, tablets, wearables, and vehicles [1]. The involved fields for these devices range from medicine and health care to fitness, from clothing to environmental monitoring [42].
In particular, one of the most affected domains is transportation and the so-called Intelligent Transport Systems (ITS) [44]. The objective of ITS is to provide a multi-modal transportation system that embraces public and private municipal, regional, national, and trans-national vehicles and fleets. This extremely heterogeneous ecosystem of transportation means is made available to the users through advanced services that can fulfill the usability requirements, while pursuing system level objectives, and which include: (i) the reduction of CO2 footprint, (ii) the real-time delivery of specific goods, (iii) the reduction of traffic within urban areas, (iv) the provisioning of pleasant journeys to tourists, and (v) the general commitment of satisfactory travel time and experience [121]. Within this context, IoT technologies can play a pivotal role. For instance, they enable advanced design paradigms (e.g., Mobility as a Service (MaaS) [41]) with significant implications on the system architecture [50] or lead to novel approaches to traffic modeling [49]. As a consequence, smart mobility support can be a significant use case scenario for ICN-IoT, where the important ICN features that corroborate mobility support are listed as follows:

* ICN is unique in that it supports both infrastructure- and ad hoc-based communications. This makes it suitable to support communication in vehicular ad hoc networks (VANETS) [19][126], along with supporting communication with the infrastructure components like the road side units to serve the needs of several smart mobility applications. ICN’s name based network APIs along with its caching feature enable the system to simultaneously operate over multiple heterogeneous radio interfaces using broadcast, unicast or anycast communication modes.

* ICN offers location independence of content, which allows one to manage consumer mobility in a simpler way than it is with IP. Furthermore, different from Mobile IP, which needs ‘triangular routing’ to locate moving hosts, ICN envisions a mobile consumer to only re-issue content requests or use network based late-binding functions once the mobile entity handoffs from one attachment point to another [45];

* In ICN, since the content is not bound to a specific location, it can be cached anywhere in the network, thereby adding redundancy to the system. In doing so, if a producer loses connectivity while it is moving, a request for its content can be resolved to an intermediate node en-route to or routed towards a nearby off-path caching node [45];
* The name based request-response communication paradigm considered for ICN decouples publish/subscribe operations in time and space. Therefore, the involved entities (i.e., publishers and subscribers) do not need to be aware of each other or be connected at the same time [46];

* The use of an in-network Name Resolution Service (NRS) design allows to identify the current location of or associated with a content name in the network, thanks to its network function, which is responsible for updating the location information of a named entity [58].

From a technological perspective, we can list the open challenges as follows: (i) support for ad hoc communications and interoperability across different IoT technologies, (ii) namespace design that is able to harmonize different ITS standards, (iii) scalable data-sharing model(s) across real-time (and non real-time) traffic sources, (iv) design of travel-centric services based on ICN-IoT, (v) seamless support to mobility, and (vi) content authentication and cryptography.

- Smart Building: Buildings are gaining smart capabilities that allow for enhanced comfort, increased safety and security, and improved energy efficiency [105]. In particular, smart buildings are no longer simple consumer(s) (for energy), but can also be prosumers with on-site energy generation systems. These systems can improve a building’s usability towards (i) smart heating, ventilation, and air conditioning (HVAC), (ii) smart lightings, (iii) plug loads, and (iv) smart windows. We can list the main requirements for these sub-systems as follows [105]: (i) context awareness, (ii) support for resource-constrained devices, (iii) interoperability across heterogeneous technologies, and (iv) security and privacy protection. The ICN paradigm can ease the fulfillment of these requirements for one simple reason: smart building services are typically information centric by design. To be specific, any time an autonomic management loop is established within a smart building to control a set of physical variables of interest, the information exchanged between the entities (e.g., users, sensors, actuators, and controllers) do not immediately translate to specific nodes within the building, but can be provided by multiple sensors or gateways. The relevance of ICN in a smart building setting is recognized in the literature as well with reference to the several frameworks deployed in various environments. For instance, in [63], nodes are distributed to different rooms, floors, and buildings of a campus university, and their energy consumption and individual behaviors are monitored. A smart home application is investigated in [107] by evaluating the retrieval delay and packet loss statistics for data.
Moreover, [108] designed and tested lighting control over NDN in a theater setting. In short, within the smart building context, we can list the ICN-specific challenges as follows: (i) design of a scalable namespace for uniquely identifying the information of interest and also host services for actuation, (ii) data-sharing model across heterogeneous systems, (iii) self-organizing functionalities for improving network connections between end-nodes, utilities and the control center, (iv) authentication procedures to grant data confidentiality and integrity.

- **Smart Grid:** Smart Grid systems are increasingly transforming into cyber-physical systems [18] with the goals of maximum automation towards efficiency and minimal human intervention. The system is a very complex one comprising of power distribution grids, end user applications (e.g., Electric Vehicle (EV) charging systems and appliances), smart monitoring systems (spanning the end users and the power grids), heterogeneous energy producing sources (including prosumers), and load distribution/balancing systems. Current smart grid systems are managed using the centralized Supervisory Control and Data Acquisition (SCADA) frameworks with highly restrictive unidirectional communication support [20]. These systems typically have the following requirements: (i) improved flexibility in distributing energy from the feeder, through real-time reconfiguration of multiple monitoring devices (e.g., phasor measurement units or PMUs) and management operations requiring an efficient data delivery infrastructure; (ii) a large scale data delivery infrastructure capable of supporting latency sensitive applications and inter-connecting heterogeneous end user devices that produce, monitor, and/or consume; (iii) resiliency, which is critical to the operation and protection of the grid; (iv) security, to protect mission critical grid applications from network intrusions; and (v) understanding machine-to-machine traffic patterns for optimal placement of storage and computing to maximize efficiency. Smart grid systems can benefit from ICN in the following ways [21][22]:

* ICN approach of naming content rather than hosts can ensure that the data generated by one subsystem would be useful for multiple entities. Furthermore, naming content can enable the many-to-many communications model, which is very inefficient in the case of host-centric architectures.

* ICN features such as in-network computing, storage, and caching enable better use of network resources and can benefit diverse application scenarios that vary from latency tolerant applications with low data rates (e.g., smart grid and energy pricing) to applications observing high data rates with stringent delay/disruption requirements (e.g., synchrophasor
measurements). Also, it is typical for smart grid systems to have applications that consume the same data at different rates, in which case in-network caching and computing can be of significant use.

* Host-centric networking exposes a mission critical infrastructure like the smart grid infrastructure to intrusion and Denial of Service (DOS) attacks, which are directly related to exposing the IP addresses of critical applications and subsystems. Naming contents, services, or devices, on the other hand, de-couples them from the location, thereby reducing the exposure to being targeted based on a geographical context.

* ICN’s name based networking offers the potential for self-configuration during both the bootstrapping phase and the regular operation of the grid, allowing scalable operation with self-recovery during faults or maintenance tasks in the system.

- Smart Industrial Automation: In a smart and connected industrial environment, equipment with sensors generate large volumes of data during normal operation. This range from the highly time-critical data for real-time control of production processes, to the less time-critical data that is collected by a central cloud environment for control room monitoring, and to pure log data without latency requirements that is mainly kept for a posteriori analysis. Industrial wireless networks are difficult environments with many potential interferences occurring at the same time even as hard reliability and real-time requirements are placed by many applications. This means that the available network capacity is not always high, so it becomes likely for traffic with less stringent delay requirements to experience congestion. One such example is, when errors occur in the production process, a mobile workforce is expected to investigate the problem on-site and they will need high resolution data from the faulty machine(s) as well as other process data from the other parts of the plant. The mobile workforces typically perform their diagnostics or maintenance locally, and they rely on the information acquired from the production system both for safety purposes and to solve any other or related issues in the plant. Furthermore, they rely on both the historical data flow (to pinpoint the root cause of the problems) and the current data flow (to assess the present state of the equipment under control). High resolution measurements are typically generated close to the mobile workforce, while the historic data has to be retrieved from the historian servers. In this scenario, multiple workers involved in the process typically access the same data, possibly with a slight time-shift. The network thus needs to support mobile users to get access to the data flows in a way suitable for their physical
location and the task requirements. Introducing ICN functionality into the system can lead to several benefits that enhance the working experience and productivity for the mobile workforce.

* When using ICN, naming of data can be done in a way that corresponds well to the current names often used in industrial scenarios as the hierarchical names defined by the OPC Foundation [10] can be easily mapped to the CCN/NDN name space.

* ICN provides the possibility to get the newest data without knowing the location of the caching nodes or whether a particular piece of data is available locally or in a central repository. ICN also gives the possibility to get either the local high-resolution data or the remote low-resolution data (as there is no need to store all the data centrally, which may not even be possible due to the large data volume). However, it may require well-defined naming conventions or routing policies that can route interests to the right location.

* ICN can reduce the network utilization as unnecessary data is not transmitted, and data accessed by multiple workers is only sent once.

* Workforce mobility between different access points in the factory can be inherently supported, without the need to maintain a connection state.

* Use of ICN can help with removing tedious configurations in clients, since that would be provided by the infrastructure.

* ICN allows the sharing of large volumes of data between users that are in physical proximity, without introducing additional traffic on the backbone network.

* Caching of data in ICN means avoiding additional accesses to a distributed redundant database in the central infrastructure with consistency requirements.

3. IoT Architectural Requirements

Future IoT platforms have to support secure interactions among a large number of heterogeneous, constrained, static or mobile resources across organization/domain boundaries. As a result, it naturally poses stringent requirements in every aspect of the system design. Below, we outline the important requirements that a future IoT platform has to address.
3.1. Naming

An important step towards realizing a unified IoT architecture is the ability to assign names that are unique to (i) each device, (ii) each data item generated by each of these devices, and (iii) each service hosted in a device or a group of devices, towards a common objective. We can assume the naming to have the following requirements. First, names need to be persistent against dynamic features that are common to IoT systems, such as lifetime, mobility, or migration. Second, names that are derived from the keys need to be self-certifying, for both device-centric and content-centric communications. For device-centric communications, binding between device names and the device must be secure. For content-centric communications, binding between the names and the content has to be secure. Third, names usually serve multiple purposes, i.e., routing, security (self-certifying), or human-readability. For IoT applications, the choice of flat versus human readable names needs to be made considering the application and network requirements such as privacy and network level scalability, resource constrained networking requirements, and the name space explosion that may occur because of the complex relationship between name hierarchies [124] that may confound application logic.

One of the challenges in naming is to ensure the trustworthiness of the names. A general approach would require a name certificate service. Such a service acts as a certificate authority in assigning names, which are themselves public keys or appropriately bound to the name for verification at the consumer end.

3.2. Security and Privacy

A variety of security and privacy concerns exist in IoT systems as they are infrastructure typically owned by private entities. For example, the unified IoT architecture makes physical objects accessible to applications across organizations and domains. Furthermore, it often integrates with a critical infrastructure and an industrial system with life safety implications, bringing with it significant security challenges and regulatory requirements [13], as will be discussed in Section 5.3. Security and privacy thus become a serious concern, as does the flexibility and usability of the design approaches. Beyond the overarching trust management challenge, security includes data integrity, authentication, and access control at different layers of the IoT architecture. Privacy includes several aspects: (i) privacy of the data producer/consumer that is directly related to each individual vertical domain such as health, electricity, etc., (ii) privacy of data content, and (iii) privacy of contextual information such as time and location of data transmission [68].
3.3. Scalability

Cisco [1] predicts that there will be around 50 Billion IoT devices on the Internet by 2020 (and these devices include sensors, Radio-Frequency IDentification (RFID) tags, and actuators), and a unified IoT platform needs to name every entity within, which includes these devices, and data and services accessed by/through them. Scalability has to be addressed at multiple levels of the IoT architecture including naming and name resolution, routing and forwarding, and security. Mobility adds further challenges in terms of scalability. Particularly, with respect to name resolution, the system should be able to register/update/resolve a name within a short latency. Additionally, scalability is also affected by the specific IoT system features such as IoT resource object count, state and rate of information update generated by the sensing devices.

3.4. Resource Constraints

IoT devices can be broadly classified as type 1, type 2, and type 3 devices, with type 1 being the most resource-constrained and type 3 being the most resource-rich [47], where the following are considered as the most typical resource types: power, computing, storage, bandwidth, and user interface.

Power constraints of IoT devices limit how much data these devices can communicate, as it has been shown that communications consume more power than other activities for embedded devices [48]. Flexible techniques to collect the relevant information are required, and uploading every single produced data to a central server is not desirable.

Computing constraints limit the type and amount of processing these devices can perform. As a result, more complex processing needs to be done at the cloud servers or at opportunistic points, for instance at the network edge, hence it is important to balance local computation versus communication costs.

Storage constraints of the IoT devices limit the amount of data that can be stored on these devices. This constraint means that unused sensor data may need to be discarded or stored in an aggregated compact form from time to time.

Bandwidth constraints of the IoT devices limit the amount of communication, hence, impose similar restrictions on the system architecture as the power constraints, i.e., one cannot afford to collect every single sensor data generated by the device and/or use complex control plane protocols. It is also worth mentioning that, this constraint also has implications on maintaining idle chatter in
the background to maintain connectivity or other volatile service state.

User interface constraints refer to whether the device is itself capable of directly interacting with a user. Possible mechanisms include, via a display and keypad, LED indicators or requires network connectivity, either locally or globally, to enable human interaction.

The above discussed resources constraints also impact application performance with respect to the end-to-end latency towards sensing or executing control loop based actuation functions.

3.5. Traffic Characteristics

IoT traffic can be broadly classified into local area traffic and wide area traffic. Local area traffic takes place among the nearby devices. For example, neighboring cars may work together to detect potential hazards on the highway, or sensors deployed in a room may collaborate to determine how to adjust the heating level in the room. These local area communications often involve data aggregation and filtering, carry real time constraints, and require fast discovery and association (for the device, data, or service). At the same time, IoT platform has to also support wide area communications. For example, in the case of Intelligent Transportation Systems, realtime video and sensor feeds from the concerned IoT entities can be used towards re-routing operations based on system state, traffic load, availability of freights, weather forecasts, and so on. Wide area communications also require efficient discovery and resolution services for data/services.

While traffic characteristics for different IoT systems are expected to be different, certain IoT systems have been analyzed and shown to have comparable uplink and downlink traffic volumes for some applications such as [2], which means that we have to optimize the bandwidth use and energy consumption in both directions. Furthermore, IoT traffic demonstrates certain periodicity and burstiness [2]. As a result, traffic characteristics of the IoT services have to be properly accounted for during system planning and provisioning.

3.6. Contextual Communication

Many IoT applications rely on dynamic contexts in the IoT system to initiate, maintain, and terminate communication among the IoT devices. Here, we refer to a context as attributes applicable to a group of devices that share some common features, such as their owners may have a certain social relationship or belong to the same...
administrative group, or the devices may be present near the same proximity. For example, cars traveling on the highway may form a "cluster" based upon their temporal physical proximity to one another as well as the detection of the same event. These temporary groups are referred to as contexts. There are two types of contexts: (i) long-term quasi-static contexts (i.e., contexts based on social contexts as well as stationary physical locations, such as sensors inside a car or a building) and (ii) short-term dynamic contexts (i.e., contexts based on temporary proximity). Between these two classes, short-term contexts are more challenging to support as they require fast formation, update, lookup and association. Therefore, in this draft, our focus will be on the more challenging latter class. In general, IoT applications need to support not only the interactions among the members of a context, but also the interactions across contexts.

3.7. Handling Mobility

There are several degrees of mobility corresponding to different IoT scenarios, ranging from static (as in fixed assets) to highly dynamic (as in vehicle-to-vehicle environments). Furthermore, mobility in an IoT architecture can refer to: (i) data producer mobility, (ii) data consumer mobility, (iii) IoT network mobility (e.g., a body-area network in motion as a person is walking), and/or (iv) disconnection between a source/destination pair (e.g., due to unreliable wireless links). The requirement on mobility support is to deliver IoT data earlier than an application's acceptable delay constraints for all the above considered cases, and if necessary, to negotiate different connectivity or security constraints specific to each mobile context. More detailed discussions on this issue are presented in Section 5.7.

3.8. Storage and Caching

Storage and caching plays a very significant role depending on the type of IoT ecosystem, which is also a function subjected to privacy and security guidelines. Caching is usually needed to increase data availability in the network and for reliability purposes, which is especially useful for wireless access scenarios and with devices experiencing intermittent connectivity to the infrastructure network. Storage is more important for an IoT system, as data is typically stored for long term analysis. Specifically, data is stored at strategic locations in the network to reduce control and computation related overheads. Depending on the application requirements, caching will strictly be driven by application level policies, considering also the privacy requirements. If, for certain type of IoT data, pervasive caching is allowed, then intermediate nodes may not need to always forward a content request to its original creator. Instead, receiving a cached copy would be sufficient for the IoT
applications. This approach may greatly reduce the content access latencies.

Considering the hierarchical nature of the IoT systems, ICN architectures can enable a flexible, heterogeneous, and potentially fault-tolerant approach to storage and caching, thereby providing contextual persistence at multiple levels. Within the context of IoT and considering the application requirements, while offering resolution to replicated stored copies, ICN can efficiently support tradeoffs between content security/privacy and regulations.

3.9. Communication Reliability

IoT applications can be broadly categorized into mission critical and non-mission critical applications. For mission critical applications, reliable communication is one of the most important features, as these applications have strong QoS requirements such as low latency and low error rates during information transfer. To support the objective of reliable communications, it is essential for an underlying system to have the following capabilities: (i) seamless mobility support under normal operating conditions, (i) efficient routing in the presence of intermittent connection loss, (iii) QoS aware routing, (iv) support for redundancy at every system level (i.e., device, service, network, storage, etc.), and (v) support for rich and diverse communication patterns, both within an IoT domain (consisting of multiple IoT nodes and one or more gateway nodes to the Internet) and across multiple such domains.

3.10. Self-Organization

Considering the scalability and efficiency requirements, the unified IoT architecture should be able to self-organize to meet various application requirements, e.g., context-driven discovery, which refers to the capability to quickly discover heterogeneous and relevant local/global devices/data/services based on the context. A publish-subscribe service, or a private trust-driven community grouping or clustering scheme, can be used to support this discovery process. For the former case, the publish-subscribe service must be implemented in a way to efficiently support seamless mobility using techniques such as in-network caching and name-based routing. For the latter case, the IoT architecture should be able to discover the private community groups/clusters in a resource efficient way.

Another aspect of self-organization is the decoupling of the sensing infrastructure from the applications. In a typical IoT deployment, various applications run on top of a vast number of IoT devices. It is not an easy task to upgrade the firmware of the IoT devices, and it is also not practical to re-program these IoT devices to
accommodate every change in these applications. Therefore, infrastructure and application specific logics need to be decoupled, and a common interface is required (i) to dynamically configure the interactions among the IoT devices and (ii) to easily modify these application logics on top of the sensing/actuating infrastructure [32] [33].

3.11. Ad hoc and Infrastructure Mode

Depending on the presence of a communication infrastructure, an IoT system can operate in an ad-hoc mode or an infrastructure mode, (or use a combination of two). For example, a vehicle may determine to report its location and status information to a server periodically through a cellular connection, or, a group of vehicles may form an ad-hoc network that collectively detects the road conditions around them. In cases, where an infrastructure is sparse, one of the participating nodes may choose to become a temporary gateway node.

The unified IoT architecture needs to design a common protocol that serves both of these modes. Such a protocol should address the challenges that may arise in them: (i) scalability and low latency for the infrastructure mode and (ii) efficient neighbor discovery and ad-hoc communication for the ad-hoc mode. Finally, we note that hybrid modes are very common in realistic IoT systems.

3.12. IoT Platform Management

Service, control and data planes for an IoT platform will be governed by its own management infrastructure, which includes (i) distributed and centralized middleware, (ii) discovery, naming, self-configuring, and analytic functions, and (iii) information dissemination, to achieve the specific IoT system objectives [27][28][29]. Towards this, new IoT management mechanisms and service metrics need to be developed to measure the success of an IoT deployment. Considering an IoT system’s defining characteristics (such as the potential to carry a large number of IoT devices, the objective to save power, mobility, and ad hoc communications), autonomous self-management schemes become very critical. Furthermore, considering its hierarchical information processing deployment model, the platform needs to orchestrate computational tasks based on the involved sensors and the available computation resources, which may change over time. An efficient resource discovery and management protocol is required to facilitate this process. The trade-off between information transmission and processing is another challenge.
4. State of the Art

Over the years, many stand-alone IoT systems have been deployed in various domains. These systems usually adopt a vertical silo architecture and support a small set of pre-designated applications. A recent trend, however, is to move away from this approach, and towards a unified IoT architecture, in which the existing silo IoT systems, as well as the new systems that are rapidly deployed, can coexist. Here, a unified architecture refers to the case, where all the application and network functions use common APIs and network protocols to interact with each other. This will make their data and services accessible to general Internet applications (which is the case for ETSI-M2M [3] and oneM2M [4] standards). In such a unified architecture, resources can be accessed over the Internet and shared across the physical boundaries of an enterprise. However, current approaches to achieve this objective are mostly based on service overlays over the Internet, whose inherent inefficiencies caused by the use of the IP protocol [58] hinders the architecture from satisfying the IoT requirements outlined earlier, particularly in terms of scalability, security, mobility, and self-organization, which are discussed in more details in Section 4.2.

4.1. Silo IoT Architecture

A typical standalone IoT system is illustrated in Figure 1, which include the devices, applications, gateway and server nodes. Many IoT devices have limited power and computing resources, unable to directly run the normal IP-based access network protocols (i.e., Ethernet, WiFi, 3G/LTE, etc.). Consequently, these devices operate over non-IP protocols to connect to the Internet servers using an IoT gateway. Through the IoT server, applications can subscribe to the data collected by these devices, or interact with them.
There have been quite a few popular protocols for standalone IoT systems, such as DF-1, MelsecNet, Honeywell SDS, BACnet, etc. However, these protocols are operating at a device-level abstraction, rather than an information driven one, leading to a fragmented information and protocol space that requires application level solutions to achieve interoperability.

4.2. Application-Layer Unified IoT Solutions

The current approach to create a unified IoT architecture is to make IoT gateways and servers adopt standard APIs. IoT devices connect to the Internet through standard APIs and IoT applications subscribe/receive data through standard control/data APIs. Built on top of today’s Internet, this application-layer unified IoT architecture is the most practical approach towards a unified IoT platform. Towards this, there are ongoing standardization efforts including ETSI[3] and oneM2M[4]. IoT service providers can then use such frameworks to build common IOT gateways and servers for their customers. In addition, IETF’s Constrained RESTful Environments (CORE) working group [5] is developing a set of protocols like Constrained Application Protocol (CoAP) [81], that is a lightweight protocol modeled after HTTP [82] and adapted specifically for the IoT. CoAP adopts the Representational State Transfer (REST) architecture with Client-Server interactions. It uses UDP as the underlying transport protocol with reliability and multicast support. Both CoAP and HTTP are considered as the suitable application level protocols for M2M communications, as well as for IoT. For example, oneM2M (which is one of the leading standards for a unified M2M architecture) has protocol bindings to both HTTP and CoAP for its primitives. Figure 2 shows the architecture adopted in this approach.
4.2.1. Weaknesses of the Application-Layer Approach

The above application-layer approach can work with many different protocols, but the system is built upon today’s IP network, which has inherent weaknesses towards supporting a unified IoT system. As a result, it cannot satisfy some of the requirements outlined in Section 3, and the reasoning for that is explained as follows:

- **Naming:** In current application-layer IoT systems, naming scheme is a host-centric one, that is, the name of a given resource/service is linked to the device that can provide it. In turn, device names are coupled to the IP addresses, which are not persistent in mobile scenarios. On the other side, in IoT systems, the same service/resource can be offered by different devices.

- **Security and Trust:** In IP, security and trust model is based on the session established between two hosts. Session-based protocols rely on the exchange of several messages to establish a secure session. Use of such protocols in constrained IoT devices can have serious consequences in terms of energy efficiency, because transmission and reception of messages are often more costly than the cryptographic operations. This problem may be amplified with the number of nodes that a constrained device has to interact with, due to increase in both the computation cost and the per-session key state managed by the constrained device. Furthermore, because of focusing on securing communication
channels rather than managing the data that needs to be secured directly, current trust management schemes can be considered to be relatively weak.

- Mobility: The application-layer approach uses IP addresses as names at the network layer, which hinders the support for device/service mobility or flexible name resolution. Furthermore, the orthogonal Layer 2/3 management, and application-layer addressing and forwarding required to deploy current IoT solutions limit the scalability and management of these systems.

- Resource Constraints: The application-layer approach requires every device to send data to an aggregator, to a gateway or to the IoT server. Resource constraints of the IoT devices, especially in power and bandwidth, can seriously limit the performance of this approach.

- Traffic Characteristics: In this approach, applications are written in a host-centric manner suitable for point-to-point communication. IoT, however, requires multicast support that is challenging for the application-layer based IoT systems today, which have only limited deployment in the current Internet.

- Contextual Communications: The application-layer based IoT approach may not react to dynamic contextual changes in a timely fashion. The main reason is that the context lists are usually kept at the IoT server and they cannot help with efficient routing of requests at the network layer.

- Storage and Caching: The application-layer approach supports application-centric storage and caching but not what ICN envisions at the network layer, or flexible storage that is enabled via name-based routing or lookups.

- Self-Organization: As the application-layer approach is bound to IP semantics, it is considered as topology-based, and, as a result, it cannot sufficiently satisfy the requirement on self-organization. In addition to the topological self-organization, IoT also requires self-organization at the data and service levels [101], which are also not supported by this approach.

- Ad hoc and Infrastructure Mode: As mentioned above, the overlay-based approach lacks self-organization and adaptation to dynamic topology changes, and, therefore, it cannot provide efficient support for the ad hoc mode of communication.
4.2.2. Relation to Delay Tolerant Networking (DTN) architecture and its suitability for IoT

In [23][24], delay-tolerant networking (DTN) has been considered to support future IoT architectures. DTN was initially developed to support information delivery in the presence of network disruptions and disconnections, but it has also been extended to support heterogeneous networks and name-based routing. The DTN Bundle Protocol is able to achieve some of these same advantages and could be beneficially used in an IoT network to, for example, decouple sender and receiver. The DTN architecture is however centered around named endpoints (or endpoint IDs), each of which usually corresponds to a host or a service, and is mainly a way to transport data, while ICN generalizes this notion to named data, hosts and services and offers ways to address IoT application [25] challenges through features such as (information) naming, discovery, request and dissemination. However, endpoint IDs can also be used to identify named content, enabling the use of the bundle protocol as a transport mechanism for an information-centric system. Such a use of the bundle protocol as a transport would still require other components from an ICN architecture such as naming conventions. However, since the exact transport is not a major focus of the issues addressed by this draft, most of the provided discussions are applicable to a generic ICN architecture.

5. ICN Design Considerations for IoT

This section outlines some of the ICN specific design considerations and challenges that must be considered when adopting an ICN design for IoT applications and systems, and describes some of the trade-offs involved to support large scale IoT deployments with diverse application requirements.

Though ICN integrates (i) abstractions at the content, service, and host levels, (ii) name-based routing, and (iii) computation, caching, and storage as part of the network infrastructure, IoT requires special considerations given the heterogeneity of devices and interfaces such as for constrained networking [63][123][125], data processing, and content distribution models to meet specific application requirements, which we identify as challenges in this section.

5.1. Naming Devices, Data, and Services

Even though the ICN approach of named data and services (i.e., device independent naming) is typically desirable when retrieving IoT data, such data-centric naming may also pose certain challenges.
- **Naming of devices**: Naming devices [127] [128] can be useful in an IoT system. For example, actuators may require clients to act on a specific node of the deployed network (to switch it on or off), or it could be necessary to access a particular device for administration purposes. This can only be achieved through a specific name that uniquely identifies the targeted network entity. Moreover, a persistent name allows a device to change its attachment point without losing its identity. A friendly way to address a device is to use a contextual hierarchical name, which is of the same type as one that is used for data objects. Also note that, through disabling of caching and request aggregation on names associated with a device, it is possible to ensure that the requests targeting that device always reach the device.

- **Size of data/service name**: Content names can have variable lengths. Since each name has to uniquely identify the content and can also include self-certifying properties (e.g., the hash of the content is bound to the name), their lengths can be quite long in relation to the size of the content itself. In particular, for specific application, content name size can even exceed the Data size. This can be the case for IoT networks with sensed values that usually consist only of a few bytes (i.e., data can be as small as a short integer in case of temperature values, or one-byte in case of control messages corresponding to an actuator state as on/off). Moreover, a name that is too long is likely to trigger fragmentation at the link layer, and create additional problems (i.e., several transmissions, increased delay and security issues). Various approaches have been investigated to handle fragmentation and reassembly issues associated with ICN packets. For instance, the work in [109] proposes to perform hop-by-hop operations, i.e., each hop fragments the packet that has to be forwarded and reassembles the packet received for further processing. This mechanism allows to efficiently handle the recovery of lost or corrupted fragments locally, thereby reducing packet delivery failures that require application-level retransmissions.

- **Hash-based content name**: Hash algorithms are commonly used to name content, in order to verify that the received content is the one requested. This is only possible in contexts, where the requested object already exists, and where there is a directory service to look up names or the names are learned through a manifest service. This approach is suitable for systems with large sized data objects, where it is important to verify the content.

- **Hierarchical names**: The use of hierarchical names, as is the case with the CCN and NDN architectures, makes it easier to create names a priori based on a predefined naming convention. It also
provides a convenient way to use the same naming scheme for device names. However, since names are not self-certifying, this will require other mechanisms for verification of object integrity. If routing is also performed on the hierarchical names, the system will lose some of its location independence and caching will mostly be done on the path towards the publisher.

- **Semantic and metadata-based content name:** A semantic-based naming approach can allow for successful retrieval of name through a set of keywords (for example, 'noise level at position X'), even if a perfect matching of the name is not available [65]. Moreover, enriching contents with metadata allows to better describe the names and to establish association between similar ones. However, this mechanism requires more advanced functionality to match such metadata in the data object to the semantics of the name (e.g., comparing the position information of an object with the position information of the requested name). The need for such (potentially) computationally heavy tasks at the intermediate nodes in the network may be considered to understand the trade-offs between application and network performance. [64] proposes a metadata-based naming approach to support ICN-IoT networking with service function identification and processing of IoT data at some vantage points in the local IoT network, before returning the processed result to the consumers.

- **Naming of services:** Similar to naming of devices or data, services can also be referred to with a unique identifier, provided by a specific device or by an authorized entity (i.e., someone assigned by a central authority as the service provider). It can also be a service provided by anyone meeting certain metadata conditions. Example of services may include content retrieval, which takes a content name or description as an input and returns the value of that content, and actuation, which takes an actuation command as an input and possibly returns a status code.

- **Trust:** Names can be used to verify the authenticity and the integrity of the data. Multiple approaches can be used to provide security functionalities through names. For instance, hierarchical, schematized, Web-of-Trust models can enable public key verification, whereas self-certifying names can enable in-network integrity checks of the name-key or name-content binding without the need of a Public Key Infrastructure (PKI) or another third party to establish whether the key is trustworthy or not. This can be realized either directly or indirectly. In the former case, the hash of the content is bound to the name. In the latter case, first, the hash of the content is signed with the secret key of the publisher, and then the public key of the publisher and the signed hash are bound to the name [46]. The hash algorithm can be
applied to the already existing contents and where there is a directory service or manifest to look up names. In case of yet-to-be-published but on-demand generated contents, the hash cannot be known a-priori, hence different trust mechanisms should be investigated. Furthermore, self-certified naming approach can hide the content semantics, thus making names less human friendly. Since trends show that users prefer to find contents through a search engine using keywords, having non-human-friendly names can be a barrier, unless the content is enriched with keywords. However, this problem does not concern M2M applications, as human-readable names may not be useful in the context of just communicating machines.

- **Flexibility:** Further challenges may arise for the hierarchical naming schema, associated with the requirements on "constructible names" and "on-demand publishing" [37][38]. The former entails that each user is able to construct the name of a desired data item through specific algorithms and that it is possible to retrieve information using partially specified names. The latter refers to the possibility of requesting a not-yet-published content, thereby triggering its creation.

- **Scoping:** From an application's point of view, scopes are used to gather related data, whereas from the network’s perspective, scopes are used to mark where the content is available [68]. For instance, nodes that are involved with caching coordination can vary according to scope [69]. As a result, scoping can be used (i) to limit propagation of requests, thereby improving resource usage efficiency by reducing bandwidth and energy consumption, and (ii) to control content dissemination thanks to access control rules, which can be different for each scope [67]. Note that, relying on scoping for security/privacy has been shown to not work all that well for IP, and is unlikely to work well for ICN either. However, scoping may be useful in certain scenarios, for instance, to limit propagation of requests and provide a simple means to attain context-sensitive communications. Finally, perimeter- and channel-based access control is often violated by the current networks to enable over-the-wire updates and cloud-based services, so scoping is unlikely to replace a need for data-centric security in ICN.

- **Confidentiality:** As names can reveal information about the nature of the communication (which may also violate the privacy requirements), mechanisms for name confidentiality should be available in the ICN-IoT architecture. To grant confidentiality protection, some approaches have been proposed in order to handle access control in an ICN naming scheme such as Attribute-Based Encryption [66] and access control delegation [67]. In the first
solution, a trusted third party assigns a set of attributes to each network entity. Then, a publisher performs the following operations in order: (i) encrypting the data with a random key, (ii) generating the metadata for the decryption phase, (iii) creating an access policy that is used to encrypt the random key, and (iv) appending the encrypted key to the content name. When the consumer receives the packet, if its attributes satisfy the hidden policy in the name, it can get the random key protected in the name and decrypt the data. The second solution introduces a new trusted network entity (i.e., Access Control Provide). In this case, when a publisher generates a content, it also creates an access control policy and send it to an Access Control Provider. This network entity stores the access control policy, to which it associates a Uniform Resource Identifier (URI). This URI is sent to the publisher and included in the advertisements of the content. Then, when a subscriber tries to access a protected content, it can authenticate himself and request authorization for the particular policy to the Access Control Provider through the URI.

5.2. Name Resolution

Inter-connecting numerous IoT entities, as well as establishing reachability to them, requires a scalable name resolution system considering several dynamic factors like mobility of end points, service replication, in-network caching, failure or migration [59] [72] [73] [95]. The objective is to achieve scalable name resolution handling static and dynamic ICN entities with low complexity and control overhead. In particular, the main requirements/challenges of a name space (and the corresponding Name Resolution System where necessary) are [52] [54]:

- Scalability: The first challenge faced by ICN-IoT name resolution system is its scalability. Firstly, the approach has to support billions of objects and devices that are connected to the Internet, many of which are crossing administrative domain boundaries. Second of all, in addition to objects/devices, the name resolution system is also responsible for mapping IoT services to their network addresses. Many of these services are based upon contexts, hence dynamically changing, as pointed out in [59]. As a result, the name resolution should be able to scale gracefully to cover a large number of names/services with wide variations (e.g., hierarchical names, flat names, names with limited scope, etc.). Notice that, if hierarchical names are used, scalability can be also supported by leveraging the inherent aggregation capabilities of the hierarchy. Advanced techniques such as hyperbolic routing [89] may offer further scalability and efficiency.
o Deployability and inter-operability: Graceful deployability and interoperability with existing platforms is a must to ensure a naming schema to gain success on the market [7]. As a matter of fact, besides the need to ensure coexistence between IP-centric and ICN-IoT systems, it is required to make different ICN-IoT realms, each one based on a different ICN architecture, to inter-operate.

o Latency: For real-time or delay sensitive M2M application, the name resolution should not affect the overall QoS. With reference to this issue it becomes important to circumvent too centralized resolution schema (whatever the naming style, i.e, hierarchical or flat) by enforcing in-network cooperation among the different entities of the ICN-IoT system, when possible [99]. In addition, fast name lookup are necessary to ensure soft/hard real time services [110][111][112]. This challenge is especially important for applications with stringent latency requirements, such as health monitoring, emergency handling and smart transportation [113].

o Locality and network efficiency: During name resolution the named entities closer to the consumer should be easily accessible (subject to the application requirements). This requirement is true in general because, whatever the network, if the edges are able to satisfy the requests of their consumers, the load of the core and content seek time decrease, and the overall system scalability is improved. This facet gains further relevance in those domains where an actuation on the environment has to be executed, based on the feedbacks of the ICN-IoT system, such as in robotics applications, smart grids, and industrial plants [101].

o Agility: Some data items could disappear while some other ones are created so that the name resolution system should be able to effectively take care of these dynamic conditions. In particular, this challenge applies to very dynamic scenarios (e.g., VANETs) in which data items can be tightly coupled to nodes that can appear and disappear very frequently.

5.3. Security and Privacy

Security and privacy is crucial to all the IoT applications including the use cases discussed in Section 2 and subjected to the information context. To exemplify this, in one recent demonstration, it was shown that passive tire pressure sensors in cars could be hacked adversely affecting the automotive system [77], while at the same time this and other car information can be used by a public traffic management system to improve road safety. The ICN paradigm is information-centric as opposed to state-of-the-art host-centric
Besides aspects like naming, content retrieval and caching, this also has security implications. ICN advocates the model of trust in content rather than a direct trust in network host mode. This brings in the concept of Object Security which is contrary to session-based security mechanisms such as Transport Layer Security (TLS)/Datagram Transport Layer Security (DTLS) prevalent in the current host-centric Internet. Object Security is based on the idea of securing information objects unlike session-based security mechanisms which secure the communication channel between a pair of nodes for unicast, (or among a set of nodes for multicast/broadcast). This reinforces an inherent characteristic of ICN networks i.e. to decouple senders and receivers. Even session based trust association can be realized in ICN [86], that offers host-independence allowing authentication and authorization to be separated from session encryption, allowing multiple endpoints to meet specific service objectives. In the context of IoT, the Object Security model has several concrete advantages. Many IoT applications have as its main objective generating data and providing some services, while the communication between two devices is a secondary task. Therefore, it makes more sense to secure IoT objects instead of securing the session between communicating endpoints. Though ICN includes data-centric security features the mechanisms have to be generic enough to satisfy multiplicity of policy requirements for different applications. Furthermore security and privacy concerns have to be dealt in a scenario-specific manner with respect to network function perspective spanning naming, name-resolution, routing, caching, and ICN-APIs. The work by the JOSE WG [83] provides solution approaches to address some of these concerns for object security for constrained devices and should be considered to see what can be applied to an ICN architecture. In general, we feel that security and privacy protection in IoT systems should mainly focus on the following aspects: confidentiality, integrity, authentication and non-repudiation, and availability. Even though, implementing security and privacy methods in IOT systems faces different challenges than in other systems, like IP. Specifically, below we discuss the challenges in the constrained and infrastructure part of the network.

- In resource-constrained nodes, energy limitation is the biggest challenge. Moreover, a node it has to deliver its data over a wireless link for a reasonable period of time on a coin cell battery. As a result, traditional security/privacy measures are impractical to be implemented in the constrained part. In this case, one possible solution might be utilizing the physical wireless signals as security measures [78] [57].

- In the infrastructure part, we have several new threats introduced by ICN-IoT [88] particularly in architectures employing name
resolution service [123]. Below we list several possible attacks to a name resolution service that is critical to ICN-IoT:

1. Each IoT device is given an ICN name. The name spoofing attack is a masquerading threat, where a malicious user A claims another user B’s name and attempts to associate it with A’s own network address NA-A, by announcing the mapping (ID-B, NA-A). The consequence of this attack is a denial of service as it can cause traffic directed for B to be directed to A’s network address.

2. The stale mapping attack is a message manipulation attack involving a malicious name resolution server. In this attack, if a device moves and issues an update, the malicious name resolution server can purposely ignore the update and claim it still has the most recent mapping. Perhaps worse, a name resolution server can selectively choose which (possibly stale) mapping to give out during queries. The result is a denial of service.

3. The third potential attack, false announcement attack, is an information modification attack that results in illegitimate resource consumption. User A, which is in network NA1, claims its ID-A binds to a different network address, (ID-A, NA2). Thus A can direct its traffic to network NA2, which causes NA2’s network resources to be consumed.

4. The collusion attack is an example of an information modification attack in which a malicious user, its network and the location where the mapping is stored collude with each other. The objective behind the malicious collusion is to allow for a fake mapping involving a false network address to pass the verification and become be stored in the storage place.

5. An intruder may insert fake/false sensor data into the network. The consequence might be an increase in delay and performance degradation for network services and applications.

- IoT data is collected and stored on such servers, which usually run learning algorithms to extract patterns from such data. In this case, it is important to adopt a framework that enables privacy-preserving learning techniques. The framework defines how data is collected, modified (to satisfy the privacy requirement), and transmitted to application developers.
5.4. Caching

In-network caching helps bring data closer to the consumers, but its usage differs in constrained and infrastructure parts of the IoT network. Furthermore, caching in ICN-IoT faces several challenges:

- Which nodes on the routing path should cache the data: According to [54], caching the data on a subset of nodes can achieve a better gain than caching it on every en-route routers. In particular, the authors propose a "selective caching" scheme to locate those routers with better hit probabilities to cache data. According to [55], selecting a random router to cache data is as good as caching the content everywhere. In [91], the authors suggest that edge caching provides most of the benefits of in-network caching but with simpler deployment. However, the existing research on this topic typically consider workloads that are analogous to today’s CDNs, rather than the workload that can be attributed to IoT applications considered here. Therefore, further work is needed to understand the appropriate caching approach for IoT applications.

- What to cache for the IoT applications: In many IoT applications, customers often access a stream of sensor data, and as a result, caching a particular sensor data for longer periods may not be beneficial. In [93], a caching scheme is proposed to ensure that older instances of the same sensor stream were first to be evicted from the cache when needed. In [57], the authors suggest to cache IoT services at the intermediate routers, and in [59], the authors suggest to cache the control information such as pub/sub lists at the intermediate nodes. In addition, it is not yet clear what caching means in the context of actuation in an IoT system. For example, it could mean caching the result of a previous actuation request (using other ICN mechanisms to suppress the repeated actuation requests within a given time period), or it could have little meaning at all if the actuation uses authenticated requests as in [92].

- Efficiency of distributed caching may be application dependent: When content popularity is heterogeneous, some content is often requested repeatedly. In this case, the network can definitely benefit from caching. Another case where caching would be beneficial is when devices with low duty cycle are present in the network and when the access to the cloud infrastructure is limited. In [93], it is also shown that there are benefits to caching in the network when edge links are lossy, in particular if the losses occur close to the content producer, as is common for the wireless IoT networks. Furthermore, IoT devices can collaborate to cache content in a manner that optimizes energy
efficiency and content availability [94]. However, using distributed caching mechanisms in the network is not useful when each object is only requested at most once, as a cache hit can only occur for the second and subsequent requests. It may also be less beneficial to have caches distributed throughout the ICN network, especially in cases when there are overlays of distributed repositories, e.g., a cloud or a Content Distribution Network (CDN), from which all clients can retrieve the data. Using ICN to retrieve data from such services may add some efficiency, but in case of dense occurrence of overlay CDN servers the additional benefit of caching in ICN nodes would be lower.

Another example is when the name refers to an object with dynamic content/state. For example, when the last value for a sensor reading is requested or desired, the returned data may change any time the sensor reading is updated. In such case, in-network caching may increase the risk of returning old or stale data.

5.5. Storage

Storage is useful for IoT systems regardless of its type, be it as a long-term storage or as a short-term storage.

In the case of long-term in-network storage, resources can be distributed among vantage points, which include the network edge and the main IoT service aggregation points such as in the data centers. The main differences, in regards to IoT-driven storage, between the two locations are the size of data, processing intelligence and heterogeneity of information that has to be dealt at these locations. Specifically, the purpose of long term storage at the edge is to analyze, filter, aggregate, and re-publish IoT data for consumption either by the parent service components or directly by the consumers. At the aggregation service points, the purpose is to re-publish the data that will be presented as part of the global pub/sub service to the interested consumers. Long term storage for IoT data also serves the purpose of backup and replication of data, which come with additional caveats. First, we need to decide on the number of replicas needed for each IoT data stream, and the storage locations for these replicas. Also note that, given that many IoT applications consume data locally, storage locations should be kept near the data sources. However, since IoT data is mostly appended to the end of a stream, instead of being updated, it becomes easier to manage these multiple replicas. Second, we need to adopt a mechanism that can efficiently route traffic to the nearest data replica. ICN provides several solutions to this problem, e.g., global name resolution service (GNRS), which can keep track of each replica’s location [58].

In the case of short-term in-network storage (where the term storage refers to a temporary buffer, when an outgoing link is not
available), the objective is to improve communication reliability, especially when network links are unreliable, such as wireless links. ICN-IoT can adopt a generalized storage-aware routing algorithm to support delay and disruption tolerant packet forwarding. In such case, each router can employ the in-network storage to facilitate store vs. forward decisions in response to varying link conditions and potential network interruptions [115]. These decisions can be based on both short-term and long-term path quality metrics. Additionally, packets along disconnected paths can be handled using a disruption tolerant networking (DTN) based approach to offer delayed delivery and replication features. In particular, each router maintains two types of topology information: (i) an intra-partition graph that is formed by collecting flooded link state advertisements, which carry fine-grained, time-sensitive information about the intra-network links, and (ii) a DTN graph that is maintained via epidemically disseminated link-state advertisements, which carry connection probabilities among all the network nodes. However, for this scenario, we observe the following challenges: (i) when and how long to store the data, and (ii) the next step after the short-term storage. In [93] the authors show that it is beneficial to store data even for shorter periods of time (and even if only a single requester exist), if the network is lossy such that retransmissions and error recovery can be done locally instead of end-to-end.

5.6. Routing and Forwarding

ICN-IoT supports both device-to-device (D2D) and device-to-infrastructure (D2I) communications. D2D communications may occur within a single IoT domain, or across IoT domains, and may involve data forwarding within the source IoT domain, in the infrastructure network, and within the destination IoT domain. D2I communications involve data forwarding within the source IoT domain and in the infrastructure network. Data forwarding within an IoT domain can adopt routing protocols such as RPL [84], AODV[85], etc, with the main challenge being the resource constraints of the IoT nodes. In order to address this challenge, we can adopt a light-weight protocol using much shorter ICN names for each communicating party within an IoT domain (see Section 5.12 for details). In such case, before a packet leaves the IoT domain, gateway node translates this short ICN name associated with the source device to its original ICN name.

At the ICN infrastructure, data forwarding can adopt one of two approaches: (i) direct name-based routing or (ii) indirect name resolution service (NRS) driven routing.

- In direct name-based routing, packets are forwarded using the name corresponding to either the data itself [95][63][74] or the name of the destination node [75]. Here, the main challenge is to keep
the state information required for data routing/forwarding at the ICN router small. This can become an especially challenging issue, if the architecture uses a flat naming scheme due to lack of aggregation capabilities.

- In indirect routing, packets are forwarded based on the locator of the destination node, which is obtained through a name resolution service. Here, name-locator binding can be done either before routing (i.e., assuming static binding) or during routing (i.e., assuming dynamic binding). In the case of static binding, router state is the same as that in traditional routers, and the main challenge is to perform name resolution fast, especially with mobile IoT devices. In the case of dynamic binding, ICN routers need to maintain a name-based routing table, and the challenge becomes keeping the state information small, while at the same time performing fast name resolution.

5.7. Mobility Management

Considering the diversity of IoT applications, mobility scenarios range from tracking sensor data from mobile human beings to large fleets of diverse mobile elements such as drones, vehicles, trucks, trains (each of which may be associated with a transport infrastructure). These mobility scenarios can take place over heterogeneous access infrastructure that ranges from short range 802.15.4 communications to cellular radios. It is therefore expected that handling information delivery in an ad hoc setting, which involves vehicles, road side units (RSU), and the corresponding infrastructure based services, shall offer more challenges. ICN architectures have been generally shown to handle consumer and producer mobility scenarios efficiently [61][129], and to be suitable for V2V scenarios [62]. Networking tools to handle mobility varies based on application requirements, which vary from delay and loss tolerant to mission critical (with stringent delay and loss requirements).

Therefore, the challenge becomes to quantify the cost associated with mobility management in both the control and the forwarding planes, to handle both static binding and dynamic binding (which enables seamless mobility) of a named resource to its location when either or both of consumer and/or producer is mobile.

During a network transaction, either the producer or the consumer may move away, and thus we need mechanisms that can handle the mobility of either or both to avoid information loss. ICN differentiates the mobility of a consumer (Case I) from that of a producer (Case II):
Case I: When a consumer moves to a new location after sending out a request for data, the data may traverse the path towards the previous point of attachment (PoA), and in doing so, leaving copies of it along that path. The data can then be retrieved by the consumer by simply reissuing its request for the data, which is a technique used by the direct routing approach. Conversely, indirect routing approach does not differentiate between consumer and producer mobility [95], as the indirect routing approach only requires an update on the NRS, which can then update the routers to re-bind the named resource to its new location, while using late-binding to route the packet from the previous PoA to the new one.

Case II: In the case of a producer that has moved, the challenge becomes managing the control overhead while searching for a new data producer (or for re-locating the initial producer) [60]. For this purpose, flooding techniques can be used to re-discover the producer, or direct routing techniques can be employed after enhancing them with the late-binding feature that enables seamless mobility [61].

5.8. Contextual Communication

ICN enables contextualized communications by allowing metadata to be included within control or application payload. Doing so can help IoT applications to adapt to different environments, thereby enabling intelligent networks that are self-configurable and intelligent networking among consumers and producers [57]. For example, let us look at the following smart transportation scenario: "James walks on an NYC street and wants to find an empty taxi closest to his location." In this example, the context is the location information corresponding to James and the taxi drivers. A context service, as an IoT middleware, processes the contextual information and bridges the gap between raw sensor information and application requirements. Alternatively, we can use naming conventions that allow applications to request content in namespaces related to their local context without requiring a specific service, such as /local/geo/mgrs/4QFJ/123/678 to retrieve objects published within a 100m grid area of 4QFJ 123 678 based on the military grid reference system (MGRS). In both cases, trust providers may emerge that can vouch for an application’s local knowledge.

However, extracting contextual information on a real-time basis can become very challenging:

First, we need to have a fast context resolution service, through which the subscribed IoT devices can continuously update their contextual information to the application (e.g., for the example
above, that would be the locations of James and the taxis). Or, in the case of a namespace driven approach, we need to have mechanisms that can query the nearest neighbor based on a given namespace on a continual basis.

- The difficulty of this challenge grows rapidly as the number of involved devices as well as the number of contexts increase.

5.9. In-network Computing

In-network computing enables ICN routers to host heterogeneous services catering to various network functions and applications needs. Contextual services for IoT networks require in-network computing, with each sensor node or ICN router implementing context reasoning [57]. Another major target for in-network computing is to filter (and cleanse) the sensed data for IoT applications, as the sensed data can be noisy [76].

Within this framework, Named Function Networking (NFN) [117] is proposed as an extension of the ICN concept to named functions, which are processed in the network, and which can be used to generate data flow processing applications (for instance, one that is well-suited to time series data processing by IoT sensing applications). Related to this is the need to support efficient function naming, with functions, input parameters, and the output result can all be encapsulated within the packet header, the packet body, or a mixture of the two (e.g. [33]). If functions are encapsulated within the packet header, naming scheme can impact (i) how a computation task is routed within the network, (ii) which IoT devices are involved with the computation task (e.g. [56]), and (iii) how a name is decomposed into smaller computation tasks and deployed in the network to achieve better performance.

Another challenge is related to how to support compute-aware routing. Default routing is typically used for forwarding requests towards the nearest cache (or source/repository) and return the matching data to the requester. Compute-aware routing, on the other hand, has a different purpose. For instance, if the computation task is for aggregating the sensed data, then the routing strategy becomes routing the data to achieve a better aggregation performance [53].

In-network computing also includes synchronization challenges. Some computation tasks, for instance, may need synchronization among sub-tasks or IoT devices. For instance, a device may not send the generated data as soon as it is available, because waiting for data from the neighbouring devices can lead to better aggregation performance. Or, some devices may choose to sleep to save energy, while waiting for the results from the neighbours. Furthermore,
while aggregating the computation results along the path, intermediate IoT devices may need to choose the results generated within a certain time window.

5.10. Self-Organization

General IoT deployments involve heterogeneous IoT systems that consist of embedded systems, aggregators and service gateways in an IoT domain. To scale the IoT deployments to a large scale, scope-based self-organization is typically required. This specifically relates to the IoT system middleware functions [122] that include (i) device bootstrapping and discovery, (ii) assigning local/global names to device and/or content, and (iii) security and trust management functions towards device authentication and data privacy. ICN based on-boarding protocols have been studied [100] and has been shown to offer significant savings compared to the existing approaches. These challenges span both the constrained devices as well as the interactions among the aggregators and the service gateways, which may need to contact external services like the authentication servers to on-board these devices. A critical performance optimization metric for these functions, while operating at scale, is to have low control/data overhead in order to maximize the energy efficiency. Furthermore, within the infrastructure part of the network, scalable name-based resolution mechanisms, pub/sub services, storage and caching, and in-network computing techniques should be studied to meet the scope-based content dissemination needs of an ICN-IoT system.

5.11. Communications Reliability

ICN offers many ingredients for reliable communication, such as multi-home interest anycast over heterogeneous interfaces, caching, and forwarding intelligence for multi-path routing that leverage state-based forwarding in protocols like CCN/NDN. However, these features have not been analyzed from the QoS perspective, when heterogeneous traffic patterns are multiplexed at a router. In general, QoS for ICN is an open area of research [125]. In-network reliability comes at the cost of a complex network layer, hence a research challenge here is to build redundancy and reliability at the network layer to handle a wide range of disruption scenarios, such as congestion, short/long term connection loss, or wireless impairments along the last mile. An ICN network should allow features such as opportunistic store-and-forward mechanisms to be enabled only at certain points in the network, as these mechanisms entail additional control/forwarding plane overheads that can adversely affect the application throughput. For additional details, see Section 5.5, for the discussion on in-network storage.
5.12. Resource Constraints and Heterogeneity

An IoT architecture should take into consideration the resource constraints of the often embedded IoT nodes. Having globally unique IDs (GUID in short) is a key feature in ICN, and these IDs may consist of tens of bytes. Each device would then have a persistent and unique ID no matter when and where it moves. It is also important for ICN-IoT to keep this feature. However, always carrying the long ID in the packet header may not be always feasible, for instance, for transmissions over a low-rate layer-2 protocol such as 802.15.4. To solve this issue, ICN can operate using a lighter-weight packet header and a much shorter locally unique ID (LUID in short). In this way, we can map a device’s long GUID to its short LUID when the packet targeting the device reaches the local area IoT domain. To cope with collisions that may occur with this mapping process, we let each domain to have its own GUID-to-LUID mapping scheme, which can be managed by a gateway deployed at the edge of the domain. Different from NAT and other existing domain- or gateway-based solutions, ICN-IoT does not change the identity of an application. The applications, either on the constrained IoT devices or on the infrastructure nodes, continue to use the long GUIDs to identify one another, while the network performs the translation, which is transparent to these applications. An IoT node carries its GUID no matter where it moves, even when it is relocated to another local IoT domain and assigned a new LUID. This ensures the global reachability under mobility, while taking into consideration the resource constraints of the embedded devices.

In addition, optimizations for the other components of the ICN-IoT system (described in earlier subsections) can lead to optimization of the energy consumption as well.

6. Differences from T2TRG

Thing-to-Thing Research Group (T2TRG) [9] is an IoT research group under IRTF, which focuses on the research challenges of realizing IoT solutions assuming IP as the narrow waist. As IP-IoT has been a research topic for over a decade and with active industry solutions, this group provides a venue to study the advanced issues related to its security, provisioning, configuration and inter-operability considering the various heterogeneous application environmens. ICN-IoT, on the other hand, is a recent research effort, where the objective is to exploit the ICN features of name based routing and security, caching, multicasting, mobility, etc. in an end-to-end manner to enable IoT services spanning all kind of networking scenarios, i.e., ad hoc, infrastructure, and hybrid scenarios. More detailed comparison of IP-IoT versus ICN-IoT is presented in Section 4.
7. Security Considerations

ICN puts security in the forefront of its design, which the ICN-IoT designs can leverage to build applications with varying security requirements. This issue has been discussed quite elaborately in this draft. However, as this is an informational draft and it does not create new considerations beyond what has been discussed.

8. Conclusions

This draft offers a comprehensive view of the benefits and design challenges of using ICN to deliver IoT services, not only because of its suitability for constraint networks but also for ad hoc and infrastructure environments. The draft begins by motivating the need for ICN-IoT by considering popular IoT scenarios and then delves into understanding the IoT requirements from both application and networking perspectives. We then discuss why the current IP-based application layer unified IoT solutions fall short of meeting these requirements, and how an ICN architecture is more suitable towards addressing the IoT service needs. We then elaborate on the design challenges in realizing an ICN-IoT architecture at scale and one that offers reliability, security, energy efficiency, mobility, self-organization among others to accommodate these varying IoT service needs.

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Abstract

In this document, a convergence layer for CCNx and NDN over IEEE 802.15.4 LoWPAN networks is defined. A new frame format is specified to adapt CCNx and NDN packets to the small MTU size of IEEE 802.15.4. For that, syntactic and semantic changes to the TLV-based header formats are described. To support compatibility with other LoWPAN technologies that may coexist on a wireless medium, the dispatching scheme provided by 6LoWPAN is extended to include new dispatch types for CCNx and NDN. Additionally, the link fragmentation component of the 6LoWPAN dispatching framework is applied to ICN chunks. In its second part, the document defines stateless and stateful compression schemes to improve efficiency on constrained links. Stateless compression reduces TLV expressions to static header fields for common use cases. Stateful compression schemes elide state local to the LoWPAN and replace names in data packets by short local identifiers.

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1. Introduction

The Internet of Things (IoT) has been identified as a promising deployment area for Information Centric Networks (ICN), as infrastructureless access to content, resilient forwarding, and intra-network data replication demonstrated notable advantages over the traditional host-to-host approach on the Internet [NDN-EXP1], [NDN-EXP2]. Recent studies [NDN-MAC] have shown that an appropriate mapping to link layer technologies has a large impact on the practical performance of an ICN. This will be even more relevant in the context of IoT communication where nodes often exchange messages via low-power wireless links under lossy conditions. In this memo, we address the base adaptation of data chunks to such link layers for the ICN flavors NDN [NDN] and CCNx.

The IEEE 802.15.4 [ieee802.15.4] link layer is used in low-power and lossy networks (see "LLN" in [RFC7228]), in which devices are typically battery-operated and constrained in resources. Characteristics of LLNs include an unreliable environment, low bandwidth transmissions, and increased latencies. IEEE 802.15.4 admits a maximum physical layer packet size of 127 octets. The maximum frame header size is 25 octets, which leaves 102 octets for the payload. IEEE 802.15.4 security features further reduce this payload length by up to 21 octets, yielding a net of 81 octets for CCNx or NDN packet headers, signatures and content.

6LoWPAN [RFC4944], [RFC6282] is a convergence layer that provides frame formats, header compression and link fragmentation for IPv6 packets in IEEE 802.15.4 networks. The 6LoWPAN adaptation introduces a dispatching framework that prepends further information to 6LoWPAN packets, including a protocol identifier for IEEE 802.15.4 payload and meta information about link fragmentation.

Prevalent Type-Length-Value (TLV) based packet formats such as in CCNx and NDN are designed to be generic and extensible. This leads to header verbosity which is inappropriate in constrained environments of IEEE 802.15.4 links. This document presents ICN LoWPAN, a convergence layer for IEEE 802.15.4 motivated by 6LoWPAN that compresses packet headers of CCNx as well as NDN and allows for
an increased payload size per packet. Additionally, reusing the dispatching framework defined by 6LoWPAN enables compatibility between coexisting wireless networks of competing technologies. This also allows to reuse the link fragmentation scheme specified by 6LoWPAN for ICN LoWPAN.

ICN LoWPAN defines a more space efficient representation of CCNx and NDN packet formats. This syntactic change is described for CCNx and NDN separately, as the header formats and TLV encodings differ largely. For further reductions, default header values suitable for constrained IoT networks are selected in order to elide corresponding TLVs. Experimental evaluations of the ICN LoWPAN header compression schemes in [ICNLOWPAN] illustrate a reduced message overhead, a shortened message airtime, and an overall decline in power consumption for typical Class 2 devices compared to uncompressed ICN messages.

In a typical IoT scenario (see Figure 1), embedded devices are interconnected via a quasi-stationary infrastructure using a border router (BR) that uplinks the constrained LoWPAN network by some Gateway with the public Internet. In ICN based IoT networks, non-local Interest and Data messages transparently travel through the BR up and down between a Gateway and the embedded devices situated in the constrained LoWPAN.

![Figure 1: IoT Stub Network](image)

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119]. The use of the term, "silently ignore" is not defined in RFC 2119.
However, the term is used in this document and can be similarly construed.

This document uses the terminology of [RFC7476], [RFC7927], and [RFC7945] for ICN entities.

The following terms are used in the document and defined as follows:

ICN LoWPAN: Information-Centric Networking over Low-power Wireless Personal Area Network

LLN: Low-Power and Lossy Network

CCNx: Content-Centric Networking Architecture

NDN: Named Data Networking Architecture

3. Overview of ICN LoWPAN

3.1. Link-Layer Convergence

ICN LoWPAN provides a convergence layer that maps ICN packets onto constrained link-layer technologies. This includes features such as link-layer fragmentation, protocol separation on the link-layer level, and link-layer address mappings. The stack traversal is visualized in Figure 2.

![Figure 2: ICN LoWPAN convergence layer for IEEE 802.15.4](image)

Section 4 of this document defines the convergence layer for IEEE 802.15.4.
3.2. Stateless Header Compression

ICN LoWPAN also defines a stateless header compression scheme with the main purpose of reducing header overhead of ICN packets. This is of particular importance for link-layers with small MTUs. The stateless compression does not require pre-configuration of global state.

The CCNx and NDN header formats are composed of Type-Length-Value (TLV) fields to encode header data. The advantage of TLVs is its native support of variable-sized data. The main disadvantage of TLVs is the verbosity that results from storing the type and length of the encoded data.

The stateless header compression scheme makes use of compact bit fields to indicate the presence of mandatory and optional TLVs in the uncompressed packet. The order of set bits in the bit fields corresponds to the order of each TLV in the packet. Further compression is achieved by specifying default values and reducing the codomain of certain header fields.

Figure 3 demonstrates the stateless header compression idea. In this example, the first type of the first TLV is removed and the corresponding bit in the bit field is set. The second TLV represents a fixed-length TLV (e.g., the Nonce TLV in NDN), so that the type and the length fields are removed. The third TLV represents a boolean TLV (e.g., the MustBeFresh selector in NDN) and is missing the type, length and the value field.

```
+---+---+---+---+---+---+---+---+
| 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | Bit field
+---+---+---+---+---+---+---+---+
   |   |             |
   `-------',       ' boolean
   |             |
+-------+--------------+-------------+
| LEN   | VALUE         | VALUE       |
+-------+--------------+-------------+
```

Figure 3: Compression using a compact bit field to encode context information.

Stateless TLV compression for NDN is defined in Section 5. Section 6 defines the stateless TLV compression for CCNx.
3.3. Stateful Header Compression

ICN LoWPAN further employs two orthogonal stateful compression schemes for packet size reductions which are defined in Section 8. These mechanisms rely on shared contexts that are either distributed and maintained in the entire LoWPAN, or are generated on-demand hop-wise on a particular Interest-data path.

The shared context identification is defined in Section 8.1. The hop-wise name compression "en-route" is specified in Section 8.2.

4. IEEE 802.15.4 Adaptation

4.1. LoWPAN Encapsulation

The IEEE 802.15.4 frame header does not provide a protocol identifier for its payload. This causes problems of misinterpreting frames when several network layers coexist on the same link. To mitigate errors, 6LoWPAN defines dispatches as encapsulation headers for IEEE 802.15.4 frames (see Section 5 of [RFC4944]). Multiple LoWPAN encapsulation headers can prepend the actual payload and each encapsulation header is identified by a dispatch type.

[RFC8025] further specifies dispatch pages to switch between different contexts. When a LoWPAN parser encounters a "Page switch" LoWPAN encapsulation header, then all following encapsulation headers are interpreted by using a dispatch table as specified by the "Page switch" header. Page 0 and page 1 are reserved for 6LoWPAN. This document uses page 2 ("1111 0010 (0xF2)") for NDN and page 3 ("1111 0011 (0xF3)") for CCNx.

The base dispatch format (Figure 4) is used and extended by CCNx and NDN in Section 5 and Section 6.

```
+---+---+--------
| C | M |
+---+---+--------
```

Figure 4: Base dispatch format for ICN LoWPAN

C: Compression

0: The message is uncompressed.
1: The message is compressed.

M: Message Type
0: The payload contains an Interest message.
1: The payload contains a Data message.

ICN LoWPAN frames with compressed CCNx and NDN messages (C=1) use the extended dispatch format in Figure 5.

```
   0 1 2 ...
   +---------+--------+
   | 1       | M |CID |
   +---------+--------+
```

**Figure 5:** Extended dispatch format for compressed ICN LoWPAN

CID: Context Identifier

0: No context identifiers are present.
1: 1..n context identifiers are present.

The encapsulation format for ICN LoWPAN is displayed in Figure 6.

```
+-------------------+----------------------------------+
+-------------------+----------------------------------+
```

**Figure 6:** LoWPAN Encapsulation with ICN-LoWPAN

IEEE 802.15.4: The IEEE 802.15.4 header.

RFC4944 Disp.: Optional additional dispatches defined in Section 5.1 of [RFC4944]

Page: Page Switch. 2 for NDN and 3 for CCNx.

ICN LoWPAN: Dispatches defined in Section 5 and Section 6.

Payload: The actual (un-)compressed CCNx or NDN message.

4.2. Link Fragmentation

Small payload sizes in the LoWPAN require fragmentation for various network layers. Therefore, Section 5.3 of [RFC4944] defines a protocol-independent fragmentation dispatch type, a fragmentation header for the first fragment, and a separate fragmentation header for subsequent fragments. ICN LoWPAN adopts this fragmentation handling of [RFC4944].
The Fragmentation LoWPAN header can encapsulate other dispatch headers. The order of dispatch types is defined in Section 5 of [RFC4944]. Figure 7 shows the fragmentation scheme. The reassembled ICN LoWPAN frame does not contain any fragmentation headers and is depicted in Figure 8.

+------...------+----...----+--------+------...-------+--------...+------...------...+------...------...+------...------...+------...------...
| IEEE 802.15.4 | Frag. 1st |  Page  |   ICN LoWPAN   | Payload  /  |
+------...------+----...----+--------+------...-------+--------...

+------...------...+------...------...+------...------...+------...------...+
| IEEE 802.15.4 | Frag. 2nd | Payload  /  |
+------...------...+------...------...+------...------...+------...------...+

+------...------...+------...------...+------...------...+------...------...+
| IEEE 802.15.4 | Frag. Nth | Payload  /  |
+------...------...+------...------...+------...------...+------...------...

Figure 7: Fragmentation scheme

+------...------...+------...------...+------...------...+------...------...+
| IEEE 802.15.4 |  Page  |   ICN LoWPAN   | Payload  /  |
+------...------...+------...------...+------...------...+------...------...+

Figure 8: Reassembled ICN LoWPAN frame

5. Space-efficient Message Encoding for NDN

5.1. TLV Encoding

The NDN packet format consists of TLV fields using the TLV encoding that is described in [NDN-PACKET-SPEC]. Type and length fields are of variable size, where numbers greater than 252 are encoded using multiple octets.

If the type or length number is less than "253", then that number is encoded into the actual type or length field. If the number is greater or equals "253" and fits into 2 octets, the type or length field is set to "253" and the number is encoded in the next following 2 octets in network byte order, i.e., from the most significant byte (MSB) to the least significant byte (LSB). If the number is greater than 2 octets and fits into 4 octets, then the type or length field is set to "254" and the number is encoded in the subsequent 4 octets in network byte order. For larger numbers, the
type or length field is set to "255" and the number is encoded in the
subsequent 8 octets in network byte order.

In this specification, compressed NDN TLVs make use of a different
TLV encoding scheme that reduces size. Instead of using the first
octet as a marker for the number of following octets, the compressed
NDN TLV scheme uses a method to chain a variable number of octets
together. If an octet equals "255 (0xFF)", then the following octet
will also be interpreted. The actual value of a chain equals the sum
of all links.

If the type or length number is less than "255", then that number is
encoded into the actual type or length field (Figure 9 a). If the
type or length number (X) fits into 2 octets, then the first octet is
set to "255" and the subsequent octet equals "X mod 255" (Figure 9
b). Following this scheme, a variable-sized number (X) is encoded
using multiple octets of "255" with a trailing octet containing "X
mod 255" (Figure 9 c).

| 0 1 2 3 4 5 6 7 |
| +---------------+
| a) | < 255 (X) | = X |
| +---------------+

| 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 |
| +-------------------------------+
| b) | 255 | < 255 (X) | = 255 + X |
| +-------------------------------+

| 0 1 2 3 4 5 6 7 |
| +---------------+
| c) | 255 | 255 | < 255 (X) | = (N * 255) + X |
| +---------------+

(N - 1)

Figure 9: Compressed NDN TLV encoding scheme

5.2. Name TLV Compression

This Name TLV compression encodes length fields of two consecutive
NameComponent TLVs into one octet, using 4 bits each. This process
limits the length of a NameComponent TLV to 15 octets. A length of 0
marks the end of the compressed Name TLV.
5.3. Interest Messages

5.3.1. Uncompressed Interest Messages

An uncompressed Interest message uses the base dispatch format (see Figure 4) and sets the C as well as the M flag to "0" (Figure 11). "resv" MUST be set to 0. The Interest message is handed to the NDN network stack without modifications.

```
 0 1 ... 7
+----------------------------------------+
| 0 | 0 | resv                      |
+----------------------------------------+
```

Figure 11: Dispatch format for uncompressed NDN Interest messages

5.3.2. Compressed Interest Messages

The compressed Interest message uses the extended dispatch format (Figure 5) and sets the C flag to "1" and the M flag to "0". In the default use case, the Interest message is compressed with the following minimal rule set:

1. The "Type" field of the outermost MessageType TLV is removed.

2. The Name TLV is compressed according to Section 5.2. For this, all NameComponents are expected to be of type GenericNameComponent. Otherwise, the message MUST be sent uncompressed.
3. The InterestLifetime TLV length is set to 2 and the time is encoded as described in Section 7. The type and length fields are elided. If a lifetime is not a valid time-value, then the lifetime is rounded up to the nearest valid time-value (see Section 7).

4. The Nonce TLV, InterestLifetime TLV and HopLimit TLV MUST be moved to the end of the compressed Interest, keeping the order 1) Nonce TLV, 2) InterestLifetime TLV and 3) HopLimit TLV.

5. The Type and Length fields of Nonce TLV, InterestLifetime TLV and HopLimit TLV are elided. The presence of each TLV is deduced from the remaining length to parse. The Nonce TLV has a fixed length of 4, the InterestLifetime TLV has a fixed length of 2 and the HopLimit TLV has a fixed length of 1. Any combination yields a distinct value that matches the remaining length to parse.

The compressed NDN LoWPAN Interest message is visualized in Figure 12.

\[ T = \text{Type}, \ L = \text{Length}, \ V = \text{Value} \]

```
+--------+--------+                    +--------+
| Msg T  | Msg L  |                    | Msg L  |
+--------+--------+--------+           +--------+
| Name T | Name L | Name V |           | Name V |
+--------+--------+--------+           +--------+--------+
| CBPfx T| CBPfx L|                    | FWDH L | FWDH V |
+--------+--------+                    +--------+--------+
| MBFr T | MBFr L |
+--------+--------+    ==>    +--------+--------+
| FWDH T | FWDH L | FWDH V |           | NONC V |
+--------+--------+--------+           +--------+--------+
| NONC T | NONC L | NONC V |           | ILT V  |
+--------+--------+--------+           +--------+
| ILT T  | ILT L  | ILT V  |           | HPL V  |
+--------+--------+--------+           +--------+
| HPL T  | HPL L  | HPL V  |
+--------+--------+--------+
| PRM T  | PRM L  | PRM V  |
+--------+--------+--------+
```

Figure 12: Compressed NDN LoWPAN Interest Message

Further TLV compression is indicated by the ICN LoWPAN dispatch in Figure 13.
CID: Context Identifier  See Figure 5.

DIG: ImplicitSha256DigestComponent TLV

0: The name does not include an ImplicitSha256DigestComponent as the last TLV.

1: The name does include an ImplicitSha256DigestComponent as the last TLV. The Type and Length fields are omitted.

PFX: CanBePrefix TLV

0: The uncompressed message does not include a CanBePrefix TLV.

1: The uncompressed message does include a CanBePrefix TLV and is removed from the compressed message.

FRE: MustBeFresh TLV

0: The uncompressed message does not include a MustBeFresh TLV.

1: The uncompressed message does include a MustBeFresh TLV and is removed from the compressed message.

FWD: ForwardingHint TLV

0: The uncompressed message does not include a ForwardingHint TLV.

1: The uncompressed message does include a ForwardingHint TLV. The Type field is removed from the compressed message.

PRM: Parameters TLV

0: The uncompressed message does not include a Parameters TLV.
1: The uncompressed message does include a Parameters TLV. The Type field is removed from the compressed message.

5.4. Data Messages

5.4.1. Uncompressed Data Messages

An uncompressed Data message uses the base dispatch format and sets the C flag to "0" and the M flag to "1" (Figure 14). "resv" MUST be set to 0. The Data message is handed to the NDN network stack without modifications.

```
+---+---+-----------------------+
| 0 | 1 |         resv          |
+---+---+-----------------------+
```

Figure 14: Dispatch format for uncompressed NDN Data messages

5.4.2. Compressed Data Messages

The compressed Data message uses the extended dispatch format (Figure 5) and sets the C flag as well as the M flag to "1". By default, the Data message is compressed with the following base rule set:

1. The "Type" field of the outermost MessageType TLV is removed.

2. The Name TLV is compressed according to Section 5.2. For this, all NameComponents are expected to be of type GenericNameComponent. Otherwise, the message MUST be sent uncompressed.

3. The MetaInfo Type and Length fields are elided from the compressed Data message.

4. If present, the FinalBlockId TLV is encoded according to Section 5.2.

5. The ContentType TLV length is set to 1. Messages with ContentTypes that require more than 1 octet MUST be sent uncompressed.

6. The FreshnessPeriod TLV length is set to 2 and the time is encoded as described in Section 7. If the freshness period is not a valid time-value, then the message MUST be sent...
uncompressed in order to preserve the security envelope of the data message.

7. The FreshnessPeriod TLV and ContentType TLV MUST be moved to the end of the compressed Data, keeping the order 1) FreshnessPeriod TLV and 2) ContentType TLV.

8. The Type and Length fields of ContentType TLV and FreshnessPeriod TLV are elided. The presence of each TLV is deduced from the remaining length to parse. The FreshnessPeriod TLV has a fixed length of 2 and the ContentType TLV has a fixed length of 1. Any combination yields a distinct value that matches the remaining length to parse.

The compressed NDN LoWPAN Data message is visualized in Figure 15.

T = Type, L = Length, V = Value

![Diagram of Compressed NDN LoWPAN Data Message]

Figure 15: Compressed NDN LoWPAN Data Message

Further TLV compression is indicated by the ICN LoWPAN dispatch in Figure 16.
CID: Context Identifier  See Figure 5.

DIG: ImplicitSha256DigestComponent TLV

0: The name does not include an ImplicitSha256DigestComponent as the last TLV.

1: The name does include an ImplicitSha256DigestComponent as the last TLV. The Type and Length fields are omitted.

FBI: FinalBlockId TLV

0: The uncompressed message does not include a FinalBlockId TLV.

1: The uncompressed message does include a FinalBlockId.

CON: Content TLV

0: The uncompressed message does not include a Content TLV.

1: The uncompressed message does include a Content TLV. The Type field is removed from the compressed message.

SIG: Signature TLV

00: The Type fields of the SignatureInfo TLV, SignatureType TLV and SignatureValue TLV are removed.

01: Reserved.

10: Reserved.

11: Reserved.
6. Space-efficient Message Encoding for CCNx

6.1. TLV Encoding

The generic CCNx TLV encoding is described in [I-D.irtf-icnrg-ccnxmessages]. Type and Length fields attain the common fixed length of 2 octets.

The TLV encoding for CCNx LoWPAN is changed to the more space efficient encoding described in Section 5.1. Hence NDN and CCNx use the same compressed format for writing TLVs.

6.2. Name TLV Compression

Name TLVs are compressed using the scheme already defined in Section 5.2 for NDN. If a Name TLV contains T_IPID, T_APP, or organizational TLVs, then the name remains uncompressed.

6.3. Interest Messages

6.3.1. Uncompressed Interest Messages

An uncompressed Interest message uses the base dispatch format (see Figure 4) and sets the C as well as the M flag to "0" (Figure 17). "resv" MUST be set to 0. The Interest message is handed to the CCNx network stack without modifications.

```
  0   1   ...   7
+---+-----------------------+
| 0 | 0 |         resv         |
+---+-----------------------+
```

Figure 17: Dispatch format for uncompressed CCNx Interest messages

6.3.2. Compressed Interest Messages

The compressed Interest message uses the extended dispatch format (Figure 5) and sets the C flag to "1" and the M flag to "0". In the default use case, the Interest message is compressed with the following minimal rule set:

1. The Type and Length fields of the CCNx Message TLV are elided and are obtained from the Fixed Header on decompression.

The compressed CCNx LoWPAN Interest message is visualized in Figure 18.
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure18.png}
\caption{Compressed CCNx LoWPAN Interest Message}
\end{figure}

Further TLV compression is indicated by the ICN LoWPAN dispatch in Figure 19.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure19.png}
\caption{Dispatch format for compressed CCNx Interest messages}
\end{figure}

\textbf{CID: Context Identifier} See Figure 5.

\textbf{VER: CCNx protocol version in the fixed header}

0: The Version field equals 1 and is removed from the fixed header.

1: The Version field is carried in-line.
FLG: Flags field in the fixed header
   0: The Flags field equals 0 and is removed from the Interest message.
   1: The Flags field is carried in-line.

PTY: PacketType field in the fixed header
   0: The PacketType field is elided and assumed to be "PT_INTEREST"
   1: The PacketType field is elided and assumed to be "PT_RETURN"

HPL: HopLimit field in the fixed header
   0: The HopLimit field is carried in-line
   1: The HopLimit field is elided and assumed to be "1"

FRS: Reserved field in the fixed header
   0: The Reserved field is carried in-line
   1: The Reserved field is elided and assumed to be "0"

PAY: Optional Payload TLV
   0: The Payload TLV is absent.
   1: The Payload TLV is present and the type field is elided.

ILT: Optional Hop-By-Hop InterestLifetime TLV
   See Section 6.3.2.1 for further details on the ordering of hop-by-hop TLVs.
   0: No InterestLifetime TLV is present in the Interest message.
   1: An InterestLifetime TLV is present with a fixed length of 2 octets and is encoded as described in Section 7. The type and length fields are elided. If a lifetime is not a valid time-value, then the lifetime is rounded up to the nearest valid time-value (see Section 7).

MGH: Optional Hop-By-Hop MessageHash TLV
See Section 6.3.2.1 for further details on the ordering of hop-by-hop TLVs.

This TLV is expected to contain a T_SHA-256 TLV. If another hash is contained, then the Interest MUST be sent uncompressed.

0: The MessageHash TLV is absent.

1: A T_SHA-256 TLV is present and the type as well as the length fields are removed. The length field is assumed to represent 32 octets. The outer Message Hash TLV is omitted.

KIR: Optional KeyIdRestriction TLV

This TLV is expected to contain a T_SHA-256 TLV. If another hash is contained, then the Interest MUST be sent uncompressed.

0: The KeyIDRestriction TLV is absent.

1: A T_SHA-256 TLV is present and the type as well as the length fields are removed. The length field is assumed to represent 32 octets. The outer KeyIdRestriction TLV is omitted.

CHR: Optional ContentObjectHashRestriction TLV

This TLV is expected to contain a T_SHA-256 TLV. If another hash is contained, then the Interest MUST be sent uncompressed.

0: The ContentObjectHashRestriction TLV is absent.

1: A T_SHA-256 TLV is present and the type as well as the length fields are removed. The length field is assumed to represent 32 octets. The outer ContentObjectHashRestriction TLV is omitted.

VAL: Optional ValidationAlgorithm and ValidationPayload TLVs

0: No validation related TLVs are present in the Interest message.

1: Validation related TLVs are present in the Interest message. An additional octet follows immediately that
handles validation related TLV compressions and is
described in Section 6.3.2.2.

EXT: Extension

0: No extension octet follows.

1: An extension octet follows immediately. Extension octets
are used to extend the compression scheme, but are out of
scope of this document.

RSV: Reserved Must be set to 0.

6.3.2.1. Hop-By-Hop Header TLVs Compression

Hop-By-Hop Header TLVs are unordered. For an Interest message, two
optional Hop-By-Hop Header TLVs are defined in
[I-D.irtf-icnrg-ccnxmessages], but several more can be defined in
higher level specifications. For a compressed representation, this
document defines the following ordering of Hop-By-Hop TLVs:

1. Interest Lifetime TLV

2. Message Hash TLV

Note: If the original Interest message includes Hop-By-Hop Header
TLVs that follow a different ordering, then the message MUST be sent
uncompressed.

6.3.2.2. Validation

<table>
<thead>
<tr>
<th>ValidationAlg</th>
<th>KeyID</th>
<th>Reserved</th>
</tr>
</thead>
</table>

Figure 20: Dispatch for Interset Validations

ValidationAlg: Optional ValidationAlgorithm TLV

0000: An uncompressed ValidationAlgorithm TLV is included.

0001: A T_CRC32C ValidationAlgorithm TLV is assumed, but no
ValidationAlgorithm TLV is included.

0010: A T_CRC32C ValidationAlgorithm TLV is assumed, but no
ValidationAlgorithm TLV is included. Additionally, a
Sigtime TLV is inlined without a type and a length field.
0011: A T_HMAC-SHA256 ValidationAlgorithm TLV is assumed, but no ValidationAlgorithm TLV is included.

0100: A T_HMAC-SHA256 ValidationAlgorithm TLV is assumed, but no ValidationAlgorithm TLV is included. Additionally, a Sigtime TLV is inlined without a type and a length field.

0101: Reserved.

0110: Reserved.

0111: Reserved.

1000: Reserved.

1001: Reserved.

1010: Reserved.

1011: Reserved.

1100: Reserved.

1101: Reserved.

1110: Reserved.

1111: Reserved.

KeyID: Optional KeyID TLV within the ValidationAlgorithm TLV

00: The KeyId TLV is absent.

01: The KeyId TLV is present and uncompressed.

10: A T_SHA-256 TLV is present and the type field as well as the length fields are removed. The length field is assumed to represent 32 octets. The outer KeyId TLV is omitted.

11: A T_SHA-512 TLV is present and the type field as well as the length fields are removed. The length field is assumed to represent 64 octets. The outer KeyId TLV is omitted.

The ValidationPayload TLV is present if the ValidationAlgorithm TLV is present. The type field is omitted.
6.4. Content Objects

6.4.1. Uncompressed Content Objects

An uncompressed Content object uses the base dispatch format (see Figure 4) and sets the C flag to "0" and the M flag to "1" (Figure 21). "resv" MUST be set to 0. The Content object is handed to the CCNx network stack without modifications.

```
  0   1            ...        7
+---+---+-----------------------+
| 0 | 1 |         resv          |
+---+---+-----------------------+
```

Figure 21: Dispatch format for uncompressed CCNx Content objects

6.4.2. Compressed Content Objects

The compressed Content object uses the extended dispatch format (Figure 5) and sets the C flag as well as the M flag to "1". By default, the Content object is compressed with the following base rule set:

1. The PacketType field is elided from the Fixed Header.

2. The Type and Length fields of the CCNx Message TLV are elided and are obtained from the Fixed Header on decompression.

The compressed CCNx LoWPAN Data message is visualized in Figure 22.
T = Type, L = Length, V = Value

```
+--------------------------+           +--------------------------+
|  Uncompr. Fixed Header   |           |   Compr. Fixed Header    |
+--------------------------+           +--------------------------+
| RCT T | RCT L | RCT V |           | RCT V |
+--------+--------+--------+           +--------+
| MSGH T | MSGH L | MSGH V |           | MSGH L | MSGH V |
+--------+--------+--------+           +--------+--------+
| MSGT T | MSGT L |
| Name T | Name L | Name V |    ==>    | EXPT V |
| PTYP T | PTYP L | PTYP V |           | PAYL L | PAYL V |
| EXPT T | EXPT L | EXPT V |           | VALG L | VALG V |
| PAYL T | PAYL L | PAYL V |           | VPAY L | VPAY V |
| VALG T | VALG L | VALG V |
| VPAY T | VPAY L | VPAY V |
+--------+--------+--------+           +--------+--------+
```

Figure 22: Compressed CCNx LoWPAN Data Message

Further TLV compression is indicated by the ICN LoWPAN dispatch in Figure 23.

```
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
| 1 | 1 |CID|VER|FLG|FRS|PAY|RCT|MGH| PLTYP |EXP|VAL|EXT|  RSV  |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```

Figure 23: Dispatch format for compressed CCNx Content objects

CID: Context Identifier  See Figure 5.

VER: CCNx protocol version in the fixed header

0: The Version field equals 1 and is removed from the fixed header.

1: The Version field is carried in-line.
FLG: Flags field in the fixed header  See Section 6.3.2.
FRS: Reserved field in the fixed header  See Section 6.3.2.
PAY: Optional Payload TLV  See Section 6.3.2.
RCT: Optional Hop-By-Hop RecommendedCacheTime TLV
   0:   The Recommended Cache Time TLV is absent.
   1:   The Recommended Cache Time TLV is present and the type as well as the length fields are elided.
MGH: Optional Hop-By-Hop MessageHash TLV
    See Section 6.4.2.1 for further details on the ordering of hop-by-hop TLVs.
    This TLV is expected to contain a T_SHA-256 TLV.  If another hash is contained, then the Content Object MUST be sent uncompressed.
   0:   The MessageHash TLV is absent.
   1:   A T_SHA-256 TLV is present and the type as well as the length fields are removed. The length field is assumed to represent 32 octets. The outer Message Hash TLV is omitted.
PLTYP: Optional PayloadType TLV
   00:  The PayloadType TLV is absent.
   01:  The PayloadType TLV is absent and T_PAYLOADTYPE_DATA is assumed.
   10:  The PayloadType TLV is absent and T_PAYLOADTYPE_KEY is assumed.
   11:  The PayloadType TLV is present and uncompressed.
EXP: Optional ExpiryTime TLV
   0:   The ExpiryTime TLV is absent.
1: The ExpiryTime TLV is present and the type as well as the length fields are elided.

RSV: Reserved Must be set to 0.

VAL: Optional ValidationAlgorithm and ValidationPayload TLVs See Section 6.3.2.

EXT: Extension See Section 6.3.2.

6.4.2.1. Hop-By-Hop Header TLVs Compression

Hop-By-Hop Header TLVs are unordered. For a Content Object message, two optional Hop-By-Hop Header TLVs are defined in [I-D.irtf-icnrg-ccnxmessages], but several more can be defined in higher level specifications. For better compression, an ordering of Hop-By-Hop TLVs is required as follows:

1. Recommended Cache Time TLV
2. Message Hash TLV

With this ordering in place, Type fields are elided from the Recommended Cache Time TLV and Message Hash TLV.

Note: If the original Content Object message includes Hop-By-Hop Header TLVs with a different ordering, then they remain uncompressed.

7. Compressed Time Encoding

This document defines a compressed TLV encoding format for time-values that is inspired from [RFC5497]. 16-bit time-codes are used to represent time-values ranging from milliseconds to days.

Time-codes are constructed using the formula:

\[ \text{time-code} := 2048 \times b + a \]

where \( a \) is the mantissa and \( b \) the exponent of a time-value that follows the form:

\[ \text{time-value} := (1 + a/2048) \times 2^b \times C \]

The least significant 11 bits of a time-code represents the mantissa \( (a) \) and the most significant 5 bits represent the exponent \( (b) \). \( C \) is set to 1/1024 seconds in order to achieve a millisecond resolution.
A time-code of all-bits zero MUST be decoded as a time-value of all-bits zero. The smallest representable time-value is thus 0 (a=0, b=0), the second smallest is ~0.9 ms (a=1, b=0), and the largest time-value is ~48 days (a=2047, b=31).

An invalid time-value (t, in seconds) MAY be rounded up to the nearest valid time-value using this algorithm:

- set b := floor(log2(t/C))
- set a := 2048 * (t / (C * 2^b) - 1)

8. Stateful Header Compression

Stateful header compression in ICN LoWPAN enables packet size reductions in two ways. First, common information that is shared throughout the local LoWPAN may be memorized in context state at all nodes and omitted from communication. Second, redundancy in a single Interest-data exchange may be removed from ICN stateful forwarding on a hop-by-hop basis and memorized in en-route state tables.

8.1. LoWPAN-local State

A context identifier (CID) is an octet that refers to a particular conceptual context between network devices and MAY be used to replace frequently appearing information, like name prefixes, suffixes, or meta information, such as Interest lifetime.

```
+---+---+---+---+---+---+---+---+
| X |         ContextID         |
+---+---+---+---+---+---+---+---+
```

Figure 24: Context Identifier.

The ContextID refers to a locally-scoped unique identifier that represents contextual state shared between sender and receiver of the corresponding frame (see Figure 24).

The initial distribution and maintenance of shared context is out of scope of this document. Frames containing unknown or invalid CIDs MUST be silently discarded.
8.2. En-route State

In CCNx and NDN, Name TLVs are included in Interest messages, and they return in data messages. Returning Name TLVs either equal the original Name TLV, or they contain the original Name TLV as a prefix. ICN LoWPAN reduces this redundancy in responses by replacing Name TLVs with single octets that represent link-local HopIDs. HopIDs are carried as Context Identifiers of link-local scope as shown in Figure 25.

```
0   1   2   3   4   5   6   7
+---+---+---+---+---+---+---+---+
| X |          HopID            |
+---+---+---+---+---+---+---+---+
```

Figure 25: Context Identifier as HopID.

A HopID is valid, if not all ID bits are set to zero and invalid otherwise. This yields 127 distinct HopIDs. If this range (1...128) is exhausted, the messages MUST be sent without en-route state compression until new HopIDs are available. An ICN LoWPAN node that forwards without replacing the name by a HopID (without en-route compression) MUST invalidate the HopID by setting all ID-bits to zero.

While an Interest is traversing, a forwarder generates an ephemeral HopID that is tied to a PIT entry. Each HopID MUST be unique within the local PIT and only exists during the lifetime of a PIT entry. To maintain HopIDs, the local PIT is extended by two new columns: HIDi (inbound HopIDs) and HIDo (outbound HopIDs).

HopIDs are included in Interests and stored on the next hop with the resulting PIT entry in the HIDi column. The HopID is replaced with a newly generated local HopID before the Interest is forwarded. This new HopID is stored in the HIDo column of the local PIT (see Figure 26).
Responses include HopIDs that were obtained from Interests. If the returning Name TLV equals the original Name TLV, then the name is entirely elided. Otherwise, the distinct suffix is included along with the HopID. When a response is forwarded, the contained HopID is extracted and used to match against the correct PIT entry by performing a lookup on the HIDo column. The HopID is then replaced with the corresponding HopID from the HIDi column prior to forwarding the response (Figure 27).

Figure 26: Setting compression state en-route (Interest).

Figure 27: Eliding Name TLVs using en-route state (data).

It should be noted that each forwarder of an Interest in an ICN LoWPAN network can individually decide whether to participate in en-route compression or not. However, an ICN LoWPAN node SHOULD use en-route compression whenever the stateful compression mechanism is activated.

Note also that the extensions of the PIT data structure are required only at ICN LoWPAN nodes, while regular NDN/CCNx forwarders outside of an ICN LoWPAN domain do not need to implement these extensions.
8.3. Integrating Stateful Header Compression

A CID appears whenever the CID flag is set (see Figure 5). The CID is appended to the last ICN LoWPAN dispatch octet as shown in Figure 28.

```
/ ... | Page | ICN LoWPAN Disp | CIDs | Payload /
/-----------------------+-----------------------/
```

Figure 28: LoWPAN Encapsulation with ICN LoWPAN and CIDs

Multiple CIDs are chained together, with the most significant bit indicating the presence of a subsequent CID (Figure 29).

```
+---------+     +---------+     +---------+
|1|     CID | --> |1|     CID | --> |0|     CID |
+---------+     +---------+     +---------+
```

Figure 29: Chaining of context identifiers.

The HopID is always included as the very first CID.

9. Implementation Report and Guidance

The ICN LoWPAN scheme defined in this document has been implemented as an extension of the NDN/CCNx software stack [CCN-LITE] in its IoT version on RIOT [RIOT]. An experimental evaluation with varying configurations is performed in [ICNLOWPAN].

The header compression performance depends on certain aspects and configurations. It works best for the following cases:

- Each name component is of GenericNameComponent type and is limited to a length of 15 bytes.
- Time-values for content freshness TLVs represent valid time-values as per Section 7. Interest lifetimes will round up to the nearest valid encoded time-value.
- Contextual state is distributed, such that long names are elided from Interest and data messages.

10. Security Considerations

Main memory is typically a scarce resource of constrained networked devices. Fragmentation as described in this memo preserves fragments and purges them only after a packet is reassembled, which requires a
buffering of all fragments. This scheme is able to handle fragments for distinctive packets simultaneously, which can lead to overflowing packet buffers which cannot hold all necessary fragments for packet reassembly. Implementers are thus urged to make use of appropriate buffer replacement strategies for fragments.

The stateful header compression generates ephemeral HopIDs for incoming and outgoing Interests and consumes them on returning Data packets. Forged Interests can deplete the number of available HopIDs, thus leading to a denial of compression service for subsequent content requests.

To further alleviate the problems caused by forged fragments or Interest initiations, proper protective mechanisms for accessing the link-layer should be deployed.

11. IANA Considerations

11.1. Page Switch Dispatch Type

This document makes use of "Page 2" from the existing paging dispatches in [RFC8025].

12. References

12.1. Normative References


12.2. Informative References


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Appendix A. Estimated Size Reduction

In the following a theoretical evaluation is given to estimate the gains of ICN LoWPAN compared to uncompressed CCNx and NDN messages.

We assume that "n" is the number of name components, "comps_n" denotes the sum of n name component lengths. We also assume that the length of each name component is lower than 16 bytes. The length of the content is given by "clen". The lengths of TLV components is specific to the CCNx or NDN encoding and outlined below.

A.1. NDN

The NDN TLV encoding has variable-sized TLV fields. For simplicity, the 1 octet form of each TLV component is assumed. A typical TLV component therefore is of size 2 (type field + length field) + the actual value.

A.1.1. Interest

Figure 30 depicts the size requirements for a basic, uncompressed NDN Interest containing a CanBePrefix TLV, a MustBeFresh TLV, an InterestLifetime TLV set to 4 seconds and a HopLimit TLV set to 6. Numbers below represent the amount of octets.

\[
\begin{align*}
\text{Interest TLV} & = 2 \\
\text{Name} & = 2 + \\
\text{NameComponents} & = 2n + \\
\text{comps_n} & = 21 + 2n + \text{comps_n}
\end{align*}
\]

Figure 30: Estimated size of an uncompressed NDN Interest

Figure 31 depicts the size requirements after compression.
Figure 31: Estimated size of a compressed NDN Interest

The size difference is:
12 + 1.5n octets.

For the name "/DE/HH/HAW/BT?", the total size gain is 18 octets, which is 46% of the uncompressed packet.

A.1.2. Data

Figure 32 depicts the size requirements for a basic, uncompressed NDN Data containing a FreshnessPeriod as MetaInfo. A FreshnessPeriod of 1 minute is assumed. The value is thereby encoded using 2 octets. An HMACWithSha256 is assumed as signature. The key locator is assumed to contain a Name TLV of length klen.
Figure 32: Estimated size of an uncompressed NDN Data

Figure 33 depicts the size requirements for the compressed version of the above Data packet.

The size difference is:
15 + 1.5n octets.

For the name "/DE/HH/HAW/BT7", the total size gain is 21 octets.
A.2. CCNx

The CCNx TLV encoding defines a 2-octet encoding for type and length fields, summing up to 4 octets in total without a value.

A.2.1. Interest

Figure 34 depicts the size requirements for a basic, uncompressed CCNx Interest. No Hop-By-Hop TLVs are included, the protocol version is assumed to be 1 and the reserved field is assumed to be 0. A KeyIdRestriction TLV with T_SHA-256 is included to limit the responses to Content Objects containing the specific key.

```
+-----------------+-----------------+-----------------+-----------------+-----------------+
| Fixed Header    | Message         | Name            | NameSegments    |
| 8               | 4               | 4 +             | 4n +            |
|                 |                 | 56 + 4n +       | comps_n         |
|                 |                 |-----------------+-----------------+
|                 |                 | KeyIdRestriction| 40              |
+-----------------+-----------------+-----------------+-----------------+
```

Figure 34: Estimated size of an uncompressed CCNx Interest

Figure 35 depicts the size requirements after compression.

```
+-----------------+-----------------+-----------------+-----------------+-----------------+
| Dispatch Page Switch | CCNx Interest Dispatch | Fixed Header   | Name            |
| 1               | 2               | 3               | 4 +             |
|                 |                 |                 | 38 + n/2 +     |
|                 |                 |                 | comps_n         |
|                 |                 |                 |-----------------+-----------------+
|                 |                 |                 | T_SHA-256       |
|                 |                 |                 | 32              |
+-----------------+-----------------+-----------------+-----------------+
```

Figure 35: Estimated size of a compressed CCNx Interest

The size difference is:
18 + 3.5n octets.

For the name "/DE/HH/HAW/BT7", the size is reduced by 53 octets, which is 53% of the uncompressed packet.
A.2.2. Content Object

Figure 36 depicts the size requirements for a basic, uncompressed CCNx Content Object containing an ExpiryTime Message TLV, an HMAC_SHA-256 signature, the signature time and a hash of the shared secret key. In the fixed header, the protocol version is assumed to be 1 and the reserved field is assumed to be 0.

\[
\begin{align*}
\text{Fixed Header} & = 8 \\
\text{Message} & = 4 \\
\text{Name} & = 4 + 4n + \text{comps}_n \\
\text{ExpiryTime} & = 12 = 124 + 4n + \text{comps}_n + \text{clen} \\
\text{Payload} & = 4 + \text{clen} \\
\text{ValidationAlgorithm} & = 56 \\
\text{KeyId} & = 56 \\
\text{SignatureTime} & = 36 \\
\text{ValidationPayload} & = 36
\end{align*}
\]

Figure 36: Estimated size of an uncompressed CCNx Content Object

Figure 37 depicts the size requirements for a basic, compressed CCNx Data.
---

**Dispatch Page Switch** = 1  
**CCNx Content Dispatch** = 3  
**Fixed Header** = 2  

---

**Name**  
**NameSegments** = \( \frac{n}{2} + \)  
**comps_n** = \( 89 + \frac{n}{2} + \)  
**comps_n + clen**

---

**ExpiryTime** = 8  
**Payload** = 1 + clen  
**T_HMAC-SHA256** = 32  
**SignatureTime** = 8  
**ValidationPayload** = 34

---

Figure 37: Estimated size of a compressed CCNx Data Object

The size difference is:  
\( 35 + 3.5n \) octets.

For the name "/DE/HH/HAW/BT7", the size is reduced by 70 octets,  
which is 40% of the uncompressed packet containing a 4-octet payload.

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Abstract

Consumer mobility is supported in ICN by design, in virtue of its connectionless pull-based communication model; producer mobility though is not natively supported. This document describes MAP-Me, an anchor-less solution to manage micro-mobility of content producers in the CCN (Content Centric Networking) and NDN (Named Data Networking) architectures, with support for latency-sensitive applications. MAP-Me consists in the combination of two data plane protocols, triggered by producer movements, and leveraging ICN named-based data plane. The main protocol consists in a lightweight FIB update process, complemented by a mechanism of local notification and scoped discovery suitable for low latency applications and fast mobility.
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1. Introduction

With the phenomenal spread of portable user devices, mobility has become a basic requirement for almost any communication network as well as a compelling feature to integrate in the next generation networks (5G). The need for a mobility-management paradigm to apply within IP networks has striven a lot of efforts in research and standardization bodies (IETF, 3GPP among others), all resulting in a complex access-dependent set of mechanisms implemented via a dedicated control infrastructure. The complexity and lack of flexibility of such approaches (e.g. Mobile IP) calls for a radically new solution dismantling traditional assumptions like tunneling and anchoring of all mobile communications into the network core. This is particularly important with the increase in rates and mobile nodes (IoT), a vast amount of which never moves.

The Information Centric Network (ICN) paradigm brings native support for mobility, security, and storage within the network architecture, hence emerging as a promising 5G technology candidate. Specifically on mobility management, ICN has the potential to relieve limitations of the existing approaches by leveraging its primary feature, the redefinition of packet forwarding based on "names" rather than "network addresses". Removing the dependence on location identifiers is a first step in the direction of removing the need for any anchoring of communications into fixed network nodes, which may considerably simplify and improve mobility management. Within the ICN paradigm, several architectures have been proposed, as reported in [SURVEY12] and [SURVEY14].

As a direct result of CCN/NDN design principles, consumer mobility is natively supported: a change in physical location for the consumer does not translate into a change in the data plane like for IP. The retransmission of requests for data not yet received by the consumer takes place without involving any signaling to the network. Producer mobility and realtime group communications present more challenges, depending on the frequency of movements, latency requirements, and content lifetime. The topology does not reflect the naming structure, and the mobility management process has to preserve key functionalities such as multipath, caching, etc. In all cases, beyond providing connectivity guarantees, additional transport-level mechanisms might be required to protect the flow performance (see [WLDR] for instance).

MAP-Me aims at tackling such problems by exploiting key CCN/NDN characteristics. Previous attempts have been made in CCN/NDN (and ICN in general) literature to go beyond the traditional IP approaches, by using the existing CCN/NDN request/data packet structures to trace producer movements and to dynamically build a
reverse-forwarding path (see [SURVEY16b] for a survey). They still rely on a stable home address to inform about producer movements or on buffering of incoming requests at the producer’s previous point of attachment (PoA), which prevents support for latency-sensitive streaming applications. The approach presented in this document makes a particular focus on this class of applications (e.g. live streaming or videoconferencing) as they have the most stringent performance requirements: negligible per-packet loss-rate and delays. In addition, they typically originate from a single producer and don’t allow for the use of caching.

MAP-Me defines a name-based mechanism operating in the forwarding plane and completely removing any anchoring, while aiming at latency minimization. Its performance and guarantees of correctness, stability and bounded stretch are analyzed in [MAPME].

2. MAP-Me overview

2.1. Anchor-less mobility management

Many efforts have been made to define mobility-management models for IP networks in the last two decades, resulting in a variety of complex, often not implemented, proposals. A survey of these approaches is proposed in [RFC6301]. Likewise, within ICN, different approaches to mobility management have been presented [SURVEY13]. Specifically for the CCN/NDN solutions, several surveys of mobility-management approaches can be found [SURVEY16a] [SURVEY16b].

We follow here the classification presented in [MAPME] which highlights their reliance on indirection/rendez-vous points. In particular, a new class of anchor-less approaches is introduced, in which the present proposal fits. Such solutions are less common and have been introduced in ICN to remove the need for anchor points in the data plane, but also in the control plane in the form of resolution or mapping services. These solutions completely remove the use of locators and extend the ICN forwarding mechanisms with mobility support.

2.2. Design principles

- *Micro-Mobility* : MAP-Me addresses micro (e.g. intra Autonomous Systems) producer mobility. Addressing macro-mobility is a non-goal of the proposal. We are focusing here on complementary mechanisms able to provide a fast and lightweight handover, preserving the performance of flows in progress.

- *Control Plane Agnostic* : MAP-Me _is control-plane agnostic as it does not rely on routing updates or path computation_, which
would be too slow and too costly, but rather works at a faster timescale propagating forwarding updates on a single path. It also leverages real-time notifications left as breadcrumbs by the producer to enable live tracking of its content prefixes and avoid buffering at intermediate nodes. MAP-Me shares the use of data plane mechanisms for ensuring connectivity with [DATAPLANE] which was originally proposed for link failures. This enables the support of high-speed mobility and real-time group applications. In addition, MAP-Me mobility updates are issued at prefix granularity, rather than content or chunk/packet granularity, to minimize signaling overhead and temporary state kept by in-network nodes, and scale to large and dynamic mobile networks.

- *Access-agnostic*: MAP-Me handles mobility at Layer 3 and is designed to be access-agnostic, to cope with highly heterogeneous wireless access and multi-homed/mobile users.

- *Decentralized and localized*: MAP-Me is designed to be fully decentralized, to enhance robustness w.r.t. centralized mobility management proposals subject to single point-of-passage problem. MAP-Me updates are localized and affect a minimum number of routers at the edge of the network to restore connectivity. This effectively realizes traffic off-load close to the end-users.

- *Transparent*: MAP-Me does not involve any name nor modifications to basic request/reply operations to be compatible with standard CCN/NDN design and to avoid issues caused by name modifications like triangular routing, caching degradation, or security vulnerabilities. It does not require consumers or producers to be aware of the mobility of the remote endpoint, nor to perform any handover prediction.

- *Robust*: to network conditions (e.g. routing failure, wireless or congestion losses, and delays), by implementing hop-by-hop retransmissions of mobility updates.

2.3. MAP-Me protocols

As a data plane protocol, MAP-Me handles producer mobility events by means of dynamic FIB updates with the objective of minimizing unreachability of the producer. It relies on the existence of a routing protocol responsible for creating/updating the FIB of all routers, possibly with multipath routes, and for managing network failures (e.g. [NLSR]).

MAP-Me is composed of:
3. Update protocol

3.1. Rationale

The rationale behind MAP-Me is that the producer announces its movements to the network for all served prefixes, by sending a special Interest packet - named Interest Update (IU) - to "itself" after it reattaches to the network. Such a message looks like a regular Interest packet named with the prefix advertised by the producer. As such, it is forwarded according to the information stored in the FIBs of traversed routers towards all previous locations of the producer known by router FIBs. A special flag carried in the header of the IU enables all routers on the path to identify the Interest as a mobility update and to process it accordingly to update their FIBs (a detailed description of the IU processing is provided in Section 5.3).

The key aspect of the proposal is that it removes the need for a stable home address by directly leveraging name-based forwarding information created by CCN/NDN routing protocols, and eventually further updated due to mobility. FIB updates are triggered by the reception of mobility updates in a fully decentralized way and allow an on-the-fly modification to point to the latest known location of the producer.

3.2. Update propagation

The role of the update process is to quickly restore global reachability of mobile prefixes with low signaling overhead, while introducing a bounded maximum path stretch (the ratio between the selected and the shortest path in terms of hops).

Let us illustrate its behavior through an example where a single producer serving prefix /p moves from position P0 to P1 and so on. Figure 1 (a) shows the initial tree formed by the forwarding paths to the name prefix /p, and on which any IU initiated by the producer will propagate.
Figure 1: IU propagation example
Figure 2: IU propagation example

(a) 

(b)
Network FIBs are assumed to be populated with routes towards P0 by a name-based routing protocol. After the relocation of the producer from P0 to P1, once the layer-2 attachment is completed, the producer issues an IU carrying the prefix /p and this is forwarded by the network toward P0 (in general, toward one of its previous locations according to the FIB state of traversed routers).

Figure 1 (b) illustrates the propagation of the IU. As the IU progresses, FIBs at intermediate hops are updated with the ingress face of the IU (Figure 2 (a) and (b)). IU propagation stops when the IU reaches P0 and there is no next hop to forward it to. The result is that the original tree rooted in P0 becomes re-rooted in P1 (Figure 3). Looking at the different connected regions (represented with dotted lines), we see that IU propagation and consequent FIB updates have the effect of extending the newly connected subtree: at every step, an additional router and its predecessors are included in the connected subtree.
3.3. Concurrent updates

Frequent mobility of the producer may lead to the propagation of concurrent updates. To prevent inconsistencies in FIBs, MAP-Me maintains a sequence number at the producer end that is incremented at each handover and associated to all sent IU packets. Network routers also keep track of such sequence number in their FIBs to validate the relative freshness of received updates. The modification of FIB entries is only triggered when the received IU carries a higher sequence number than the locally stored one, while the reception of a less recent update triggers the transmission of a more up-to-date IU backwards in order to fix the not-yet-updated path.

An example reconciliation of concurrent updates is illustrated in Figure 4 (a), when the producer has moved successively to P1 and then to P2 before the first update could complete.

Both updates propagate concurrently until the one with sequence number 1 (IU(1)) crosses a router that has been updated with fresher information. In the example shown in Figure 4 (b), the junction router has already received an IU with higher sequence number (IU(2)). In this case, the router stops the propagation of IU(1) and sends back along its path a new IU with an updated sequence number (Figure 5 (a)). The update proceeds until the whole network has ultimately converged towards P2 (Figure 5 (b)).

MAP-Me protocol reacts at a faster timescale than routing - allowing more frequent and numerous mobility events - and over a localized portion of the network edge between current and previous producer locations. This allows to minimize disconnectivity time and reduce link load, which are the main factors affecting user flow performance, as shown in [MAPME] evaluations.
4. Notification protocol and scoped discovery

IU propagation in the data plane is designed to accelerate forwarding state re-convergence w.r.t. routing or resolution-based approaches operating at control plane, and w.r.t. anchor-based approaches requiring traffic tunneling through an anchor node. Still, network latency makes IU completion not instantaneous and before an update completes, it may happen that a portion of the traffic is forwarded to the previous PoA and dropped because of the absence of a valid output face leading to the producer.

Previous work in the Anchor-Less category has suggested the buffering of Interests at previous producer location to prevent those losses. However, such a solution is not suitable for applications with stringent latency requirements (e.g. real-time) and may be incompatible with IU completion times. Moreover, the negative effects on latency performance might be further exacerbated by IU losses and consequent retransmissions in case of wireless medium. To alleviate such issues, we introduce two enhancements to the previously described behavior, namely (i) an "Interest Notification" mechanism for frequent, yet lightweight, signaling of producer movements to the network and (ii) a scoped "Producer Discovery" mechanism for consumer requests to proactively search for the producer’s recently visited locations.

4.1. Interest Notification

An Interest Notification (IN) is a breadcrumb left by producers at every encountered PoA. It looks like a normal Interest packet carrying a special identification flag and a sequence number, like IUs. Both IU and IN share the same sequence number (producers indistinctly increase it for every sent message) and follow the same FIB lookup and update processes. However, unlike IU packets, the trace left by INs at the first hop router does not propagate further. It is rather used by the discovery process to route consumer requests to the producer even before an update process is completed.

It is worth observing that updates and notifications serve the same purpose of informing the network of a producer movement. The IU process restores connectivity and as such has higher latency/signaling cost than the IN process, due to message propagation. The IN process provides information to track producer movements before update completion when coupled with a scoped discovery. The combination of both IU and IN allows to control the trade-off between protocol reactivity and stability of forwarding re-convergence.
4.2. Scoped discovery

The extension of MAP-Me with notifications relies on a local discovery phase: when a consumer Interest reaches a PoA with no valid output face in the corresponding entry, the Interest is tagged with a "discovery" flag and labeled with the latest sequence number stored in FIB (to avoid loops). From that point on, it is broadcasted with hop limit equal to one to all neighbors and discarded unless it finds a breadcrumb left by the producer with a higher sequence number. The notifications can either allow to forward consumer Interests directly to the producer or give rise to a repeated broadcast in case of no valid output face. The latter is the case of a breadcrumb left by the producer with no associated forwarding information because the producer has already left that PoA as well. A detailed description of the process is reported in Section 5.3.

The notification/discovery mechanism proves important to preserve the performance of flows in progress, especially when latency-sensitive.

4.3. Full approach

The full MAP-Me approach consists in the combination of Updates and Notifications through a heuristic allowing the producer or its PoA to select which type of packet to send. One such heuristic consist in sending a IN immediately after an attachment and a IU at most every Tu seconds, which allows to reduce signaling overhead during periods of high-mobility. The Tu parameter allows to tune the timescale at which Updates occur, and leads to a trade-off between signaling and discovery overhead [MAPME]. The definition of more advanced heuristics is out of scope for the present draft.

5. Implementation

In this section we describe the changes to a regular CCN/NDN architecture required to implement MAP-ME and detail the above-described algorithms. This requires to specify a special Interest message, additional temporary information associated to the FIB entry and additional operations to update such entry.

5.1. MAP-Me messages

MAP-Me signaling messages are carried within user plane as special Interest messages corresponding to "update" and "notification", and their corresponding acknowledgements.

Two new optional fields are introduced in a CCN/NDN Interest header:
o an "Interest Type" (T) used to specify one of the four types of messages: Interest Update (IU), Interest Notification (IN), and as well as their associated acknowledgment (Ack) messages (IU_Ack and IN_Ack). Those flags are recognized by the forwarding pipeline to trigger special treatment;

o a "sequence number" to handle concurrent updates and prevent forwarding loops during signaling, and to control discovery Interests’ propagation;

5.2. Data structures and temporary state

FIB entries are augmented with information required for mobility management, that we denote as Transient FIB buffer, or simply TFIB, and sketch in Figure 6:

o a "sequence number" which is incremented upon reception of IU/IN messages. It can be assumed this counter is set to 0 by the routing protocol.

o a list of so-called "previous next hop(s)" (further denoted as PrevHops), similar to the list of NextHops in the original FIB, which temporarily stores information about faces that were previously next hops, and should still be memorized to allow for retransmissions and thus ensure the consistency of MAP-Me operations. They typically correspond to nodes for which an IU has been sent, but no acknowledgement (ACK) has yet been received (upon which they are cleared). In case of notifications, no ACK is expected, and those entries serve as a memory of the former tree structure that will be restored upon producer departure. We flag those entries with a boolean marker indicating if they correspond to an IU (and thus should be monitored for retransmissions) or an IN (in which case they just serve as memory for further use).

```
IU (IN) input face(s)   IU (IN) output face
+------------------------+------------------------+
| /prefix               | { next hop(s) }        |
| /---------------------+------------------------|
|                      | seq                    |
|                      | { previous next hop(s) }|
+------------------------+------------------------+
                           
V                          V
original FIB              TFIB section
```

Figure 6: MAP-Me FIB/TFIB description
5.3. Algorithm description

5.3.1. Producer attachment and face creation

MAP-Me operations are triggered by a change of adjacencies in the network, reflected in the forwarder by the creation or removal of a face. This can be for instance the layer 2 detachment and attachment following a mobility/handover event, but also any other mechanism such as point-to-point IP link or UDP tunnel for instance, as allowed by the forwarder implementation.

One realization of this architecture is to delegate face management to a third party agent, keeping the ICN forwarder state synchronized with the underlying topology, and having MAP-Me only react to changes in the face table.

5.3.2. IU/IN transmission at producer

The creation of a new face on the producer triggers the increase of MAP-Me sequence number and the transmission for every locally served prefix, of an IU or IN carrying the updated sequence number.

5.3.3. IU/IN transmission at network routers

At the reception of IU/IN packets, each router performs a name-based Longest Prefix Match lookup in FIB to compare sequence number from IU/IN and from FIB. According to that comparison:

- if the IU/IN packet carries a higher sequence number, the existing next hops associated to the lower sequence number in FIB are used to forward further the IU (INs are not propagated) and temporarily copied into TFIB to avoid loss of such information before completion of the IU/IN acknowledgement process. The ingress face of the IU/IN is then added to FIB to route consumer requests to the latest known location of the producer.

- If the IU/IN packet carries the same sequence number as in the FIB, the originating face of the IU/IN is added to the existing ones in FIB without additional packet processing or propagation. This may occur in presence of multiple forwarding paths.

- If the IU/IN packet carries a lower sequence number than the one in the FIB, FIB entry is not updated as it already stores ‘fresher information’. To advertise the latest update through the path followed by the IU/IN packet, this one is re-sent through the originating face after having updated its sequence number with the value stored in FIB.
The operations in the forwarding pipeline for IU/IN processing are reported in Figure 7, where we make use of the following primitives:

- Send(Interest, Face) is used to send the specified Interest on the specified Face.
- ProcessTFIB() sends an IU for all flagged entries in the TFIB, using the latest sequence number stored in the FIB entry, and schedule the entry to be checked for retransmissions.

```
Algorithm 1: ForwardSpecialInterest(SpecialInterest SI, IngressFace F)
```

```
CheckValidity()
  // Acknowledge reception
  s <- e.seq
  e.seq <- SI.seq
  Send(IU_Ack(e.seq), F)
  flag <- (SI.type == IU)
  // Retrieve the FIB entry associated to the prefix
  e <- FIB.LongestPrefixMatch(SI.name)
  if SI.seq >= e.seq then
    // Process special interest
    e.TFIB = e.TFIB \ { F }
    if SI.seq > s then
      . e.TFIB = e.TFIB U { (f, flag) | f in (e.NextHops \ F) }
      . ProcessTFIB()
    . e.NextHops = {}
    . e.NextHops = e.NextHops U { F }
  else
    . // Send updated IU backwards
    . SI.seq = e.seq
    . e.TFIB = e.TFIB U { (F, flag) }
    . ProcessTFIB()
```

Figure 7

### 5.3.4. Reliable transmission

MAP-Me ensure the reliable delivery of signaling messages thanks to a retransmission timer which reissue Interest Updates (eventually carrying updated sequence number as found in the FIB), if no corresponding ACK has been received in a predefined interval, and whose sequence number has to match the one stored in the FIB.

A slotted implementation of such scheme is possible by using a single timer, and keeping a list of FIB entries that require to be checked for pending retransmissions in the next slot. Upon timer expiration, if all required ACKs have been received, the TFIB will be empty and the entry does not have to be tracked anymore. Otherwise, necessary retransmissions are performed and the entry will be checked again in
the next slot. When no entry has to be monitored, the process can sleep until the next mobility event.

5.3.5. Consumer request forwarding in case of producer discovery

The forwarding of regular Interests is mostly unaffected in MAP-Me, except in the case of discovery Interests that we detail in Figure 8. The function SendToNeighbors(I) is responsible for broadcasting the Interest I to all neighboring PoAs.

Algorithm 2: InterestForward(Interest I, Origin face F)

```
// Regular PIT and CS lookup
e ← FIB.LongestPrefixMatch(I.name)
if e = 0 then
    return
if I.seq = 0 then
    // Regular interest
    if hasValidFace(e.NextHops) or DiscoveryDisabled then
        ForwardingStrategy.process(I, e)
    else
        // Enter discovery mode
        I.seq ← e.seq
        SendToNeighbors(I)
    else
        // Discovery interest: forward if producer is connected
        if hasProducerFace(e.NextHops) then
            ForwardingStrategy.process(I, e)
        else
            // Otherwise iterate if higher seq and breadcrumb
            if e.seq >= I.seq and EXISTS f |(f -> NULL) in e.TFIB then
                I.seq ← e.seq
                SendToNeighbors(I)
```

Figure 8

When an Interest arrives to a PoA which has no valid next hop for it (because the producer left and the face got destroyed), it enters a discovery phase where the Interest is flagged as a Discovery Interest and with the local sequence number, then broadcasted to neighboring PoAs.

Upon reception of a Discovery Interest, the PoA forwards it directly to the producer if still attached, otherwise it repeats the one-hop broadcast discovery to neighboring PoAs if it stores a recent notification of the producer presence, i.e. an entry in TFIB having higher sequence number than the one in the Discovery Interest. Otherwise, the Discovery Interest is discarded.
It is worth observing that the discovery process is initiated only in the case of no valid next hop, and not every time a notification is found in a router. This is important to guarantee that the notification/discovery process does not affect IU propagation and completion.

5.3.6. Producer departure and face destruction

Upon producer departures from a PoA, the corresponding face is destroyed. If this leads to the removal of the last next hop, then faces in TFIB corresponding to IN are restored as next hops in the FIB so as to preserve the original forwarding tree and thus global connectivity.

6. Security considerations

All mobility management protocols share the same critical need for securing their control messages which have a direct impact on the forwarding of users’ traffic. [SEC] reviews standard approaches from the literature and proposes a fast, lightweight and decentralized approach based on hash chains that can be applied to MAP-Me and fits its design principles.

7. Acknowledgements

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8. IANA Considerations

This memo includes no request to IANA.

9. References

9.1. Normative References


9.2. Informative References

[DATAPLANE]


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ICN Ping Protocol Specification
draft-mastorakis-icnrg-icnping-04

Abstract

This document presents the design of an ICN Ping protocol. It includes the operations both on the client and the forwarder side.

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Determining data plane reachability to a destination and taking coarse performance measurements of round trip time are fundamental facilities for network administration and troubleshooting. In IP, where routing and forwarding are based on IP addresses, ICMP echo and ICMP echo response are the protocol mechanisms used for this purpose, generally exercised through the familiar ping utility. In ICN, where routing and forwarding are based on name prefixes, the ability to determine reachability of names is required.

This document proposes protocol mechanisms for a ping equivalent in ICN networks. A non-normative appendix suggests useful properties for an ICN ping client application, analogous to IP ping, that originates echo requests and process echo replies.

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 Ping Operation

In IP-based ping, an IP address is specified, either directly, or via translation of a domain name through DNS. The ping client application sends a number of ICMP Echo Request packets with the specified IP address as the IP destination address and an IP address from the client’s host as the IP source address.

An ICMP Echo Request is forwarded across the network based on its destination IP address. If it eventually reaches the destination, the destination responds by sending back an ICMP Echo Reply packet to the IP source address from the ICMP Echo Request.

If an ICMP Echo Request does not reach the destination or the Echo reply is lost, the ping client times out. Any ICMP error messages, such as "no route to destination", generated by the ICMP Echo Request message are returned to the client and reported.

3. Ping Functionality Challenges and Opportunities in ICN

In ICN protocols (e.g., NDN and CCNx), 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).

IP-based ping was built as an add-on on top of an already existing network architecture. In ICN, we have the opportunity to incorporate diagnostic mechanisms directly in the network layer protocol, and hopefully provide more powerful diagnostic capability than can be realized through the layered ICMP Echo approach.

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 hierarchical 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. This can lead to a significant variance in round-trip times, which might not be desirable in the case of a network troubleshooting mechanism like ping.

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 an ICN ping protocol. Following this communication model, a ping client should be able to express ping echo requests with some name prefix and receive responses.

Our goals are the following:

- Test the reachability and the operation of an ICN forwarder.
- Test the reachability of an application (in the sense of whether Interests for a prefix that it serves can be forwarded to it) and discover the forwarder with local connectivity to (an instance of) the application.
- Test whether a specific named object is cached in some on-path CS, and, if so, return the administrative name of the corresponding forwarder.
- Perform some simple network performance measurements.

To this end, a ping name can represent:

- An administrative name that has been assigned to a forwarder.
o A name that includes an application’s namespace as a prefix.

o 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 ping echo request enable the forwarders to distinguish a ping 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 ping echo reply should allow for forwarder processing as close as possible to that used for data packets.

The ping protocol should also enable relatively robust round-trip time measurements. To this end, it is important to have a mechanism to steer consecutive ping echo requests for the same name towards an individual path [PATHSTEERING].

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

4. ICN Ping Echo CCNx Packet Formats

In this section, we describe the Echo Packet Format according to the CCNx packet format [CCNMessages], where messages exist within outermost containments (packets). Specifically, we propose two types of ping packets, an echo request and an echo reply packet type.

4.1. ICN Ping Echo Request CCNx Packet Format

The format of the ping echo request packet is presented below:
Echo Request CCNx Packet Format

The existing packet header fields have the same definition as the header fields of a CCNx Interest packet. The value of the packet type field is Echo Request. The exact numeric value of this field type is to be assigned in the Packet Type IANA Registry for CCNx (see section 4.1 of [CCNMessages]).

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 PathSteering hop-by-hop header TLV, which is constructed hop-by-hop in the echo reply and included in the echo request to steer consecutive echo requests expressed by a ping client towards a common forwarding path. An example of such a scheme is presented in [PATHSTEERING].
PathSteering TLV

The message of an echo request is presented below:

```
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
```

<table>
<thead>
<tr>
<th>getMessageType</th>
<th>MessageLength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Name TLV

Echo Request Message Format

The echo 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 prefix that we would like to ping appended with a nonce typed name component as its last component. The exact numeric value of this field type is to be assigned in the Name Component Type IANA Registry for CCNx (see section 4.5 of [CCNMessages]). The value of this TLV is a 64-bit nonce. The purpose of the nonce is to avoid Interest aggregation and allow client matching of replies with requests. As described below, the nonce is ignored for CS checking.
Nonce Typing Name Component TLV

4.2. Ping Echo Reply CCNx Packet Format

The format of a ping echo reply packet is presented below:

```
01234567890123456789012345678901
```

```
+---------------+---------------+---------------+---------------+
|               |               |               |               |
| Version        | EchoReply     | PacketLength  |
| Reserved       | Flags         | HeaderLength  |
|                |               |               |
+---------------+---------------+---------------+---------------+
| PathSteering TLV |               |               |
+---------------+---------------+---------------+---------------+
| Echo Reply Message TLVs |
+-------------------+
```

Echo Reply CCNx Packet Format
The header of an echo reply consists of the header fields of a CCNx Content Object and a hop-by-hop PathSteering TLV. The value of the packet type field is Echo Reply. The exact numeric value of this field type is to be assigned in the Packet Type IANA Registry for CCNx (see section 4.1 of [CCNMessages]). The PathSteering header TLV is as defined for the echo request packet.

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

The PayloadType TLV is presented below. It is of type T_PAYLOADTYPE_DATA, and the data schema consists of 3 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 a return code to indicate what led to the generation of this reply (i.e., existence of a local application, a CS hit or a match with a forwarder’s administrative name as specified in Section 6).
Echo Reply Message Format

The goal of including the name of the sender in the echo reply is to enable the user to reach this entity directly to ask for further management/administrative information using generic Interest-Data exchanges or by employing a more comprehensive management tool such as CCNInfo [CCNInfo] after a successful verification of the sender’s name.

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

- 1: Indicates that the target name matched the administrative name of a forwarder.
- 2: Indicates that the target name matched a prefix served by an application.
- 3: Indicates that the target name matched the name of an object in a forwarder’s CS.
Echo Reply Code TLV

5. ICN Ping Echo NDN Packet Formats

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

5.1. ICN Ping Echo Request NDN Packet Format

An echo request is encoded as an NDN Interest packet. Its format is the following:

```
EchoRequest ::= INTEREST-TYPE TLV-LENGTH
              Name
              MustBeFresh
              Nonce
              Parameters?
```

The name of an echo request consists of the prefix to be pinged, a nonce value (it can be the value of the Nonce field) and the suffix "ping" to denote that this Interest is a ping request.

The "Parameters" field of the Request contains the following PathSteering TLV:

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

PathSteering TLV

Since the NDN packet format does not provide a mechanism to prevent the network from caching specific data packets, we use the MustBeFresh selector for echo requests (in combination with a
Freshness Period TLV of value 0 for echo replies) to avoid fetching cached echo replies with an expired freshness period [REALTIME].

5.2. Ping Echo Reply NDN Packet Format

An echo reply is encoded as an NDN Data packet. Its format is the following:

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

Echo Reply NDN Packet Format

Compared to the format of a regular NDN Data packet, an echo 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 an echo reply is the name of the corresponding echo 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 an echo reply consists of the following 2 TLVs: Sender's name (with a structure similar as an NDN Name TLV) and Echo 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 Echo Reply Code TLV format is the following (with the values specified in Section 4.2):

```
EchoReplyCode ::= ECHOREPLYCODE-TLV-TYPE TLV-LENGTH BYTE(2)
```

Echo Reply Code TLV
6. Forwarder Handling

When a forwarder receives an echo request, it first extracts the message’s base name (i.e., the request name with the Nonce name component excluded and the suffix "ping" in the case of an echo request with the NDN packet format).

In some cases, the forwarder originates an echo reply, sending the reply downstream through the face on which the echo request was received. This echo reply includes the forwarder’s own name and signature and the appropriate echo reply code based on the condition that triggered the reply generation. It also includes a pathSteering TLV, initially containing a null value (since the echo reply originator did not forward the request and, thus, does not make a path choice).

The forwarder generates and returns an echo reply in the following cases:

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

If none of the conditions to reply to the echo request are met, the forwarder will attempt to forward the echo request upstream based on the path steering value (if present), the results of the FIB LPM lookup and PIT creation (based on the name including the nonce typed name component and the suffix "ping" in the case of an echo request with the NDN packet format). If no valid next-hop is found, an InterestReturn is sent downstream indicating "no route" (as with a failed attempt to forward an ordinary Interest).

A received echo reply will be matched to an existing PIT entry as usual. On the reverse path, the path steering TLV of an echo reply will be updated by each forwarder to encode its next-hop choice. When included in subsequent echo requests, this pathSteering TLV allows the forwarders to steer the echo 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 pinged 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 ping 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 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 depends on various network design factors and is out of the scope of the current draft.

Based on the current usage of the LINK Object by the NDN team, a forwarder at the border of the region where an Interest name becomes routable must remove the LINK Object from 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 its name or a routable 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 echo requests expressed by the client. In this way, a request will be forwarded based on the routable part of its name. When it reaches the network region where the original locally-scoped name is routable, the border forwarder rewrites the request name and deletes 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. Within the network region that the locally-scoped prefix is routable, the state is based only on it. To ensure that the generated replies reach the ping client, the border forwarder has also to rewrite the name of a reply and prepend the routable prefix of the corresponding echo request.
8. Security Considerations

A reflection attack could in the case of an echo reply with the CCNx packet format if a compromised forwarder includes in the reply the name of a victim forwarder. This could redirect the future administrative traffic towards the victim. To foil such reflection attacks, the forwarder that generates a reply must sign the name included in the payload. In this way, the client is able to verify that the included name is legitimate and refers to the forwarder that generated the reply. Alternatively, the forwarder could include in the reply payload their routable prefix(es) encoded as a signed NDN Link Object [SNAMP].

Interest flooding attack amplification is possible in the case of the second approach to deal with locally-scoped namespaces described in Section 7. To eliminate such amplification, a border forwarder will have to maintain extra state in order 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.

9. Acknowledgements

The authors would like to thank Mark Stapp for the fruitful discussion on the objectives of the ICN ping protocol.

10. References

10.1. Normative References


10.2. Informative References

Appendix A.  Ping Client Application (Consumer) Operation

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

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

When generating a series of echo requests for a specific name, the first echo request will typically not include a PathSteering TLV, since no TLV value is known. After an echo reply containing a PathSteering TLV is received, each subsequent echo request can include the received path steering value in the PathSteering header TLV to drive the requests towards a common path as part of checking network performance. To discover more paths, a client can omit the path steering TLV in future requests. Moreover, for each new ping echo 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 an echo request, which will have identical semantics to the lifetime of an Interest.

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

When it receives an echo 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 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). The client can also decode the Echo Reply Code TLV to understand the condition that triggered the generation of the reply.

In the case that an echo 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 some maximum number of requests to be sent specified by the user.

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ICN Traceroute Protocol Specification
draft-mastorakis-icnrg-icntraceroute-04

Abstract

This document presents the design of an ICN Traceroute protocol. This includes the operations both on the client and the forwarder side.

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1. Introduction

In TCP/IP, routing and forwarding are based on IP addresses. To ascertain the route to an IP address and to measure the transit delays, the traceroute utility is commonly used. In ICN, routing and forwarding are based on name prefixes. To this end, the problem of ascertaining the characteristics (i.e., transit forwarders and delays) of at least one of the available routes to a name prefix is a fundamental requirement for instrumentation and network management.

This document describes protocol mechanisms for a traceroute equivalent in ICN networks based on CCN or NDN. This document contains a non-normative appendix section suggesting useful properties for an ICN traceroute client application that originates traceroute requests and processes traceroute replies.

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, responds by sending back an ICMP Time Exceeded packet, unless explicitly prevented from doing so by a security policy.

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 substantially different approach is 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 hierarchical 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 ability to discover multiple available (or potentially all) paths towards a name prefix is a desirable capability 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 even under constant network load.

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 directed to a 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 toward 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 identity of the corresponding forwarder.

- Perform transit delay network measurements.

To this end, a traceroute target name can represent:
o An administrative name that has been assigned to a forwarder. Assigning a name to a forwarder implies the presence of a management application running locally, which handles Operations, Administration and Management (OAM) operations.

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

o 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 enable the forwarders to distinguish this request from a normal Interest, while also preserving forwarding behavior as similar as possible to that for an Interest packet. In the same way, the encoding of a traceroute reply should allow for processing as similar as possible 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 is desirable that ICN traceroute be 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. The mechanism described in [PATHSTEERING] can be used for this purpose.

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 traceroute reply packet type.
4.1. ICN Traceroute Request CCNx Packet Format

The format of the traceroute request packet is presented below:

```
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
```

+---------------+---------------+---------------+---------------+
|               |               |               |               |
|    Version    |   TrRequest   |         PacketLength          |
|               |               |               |               |
+---------------+---------------+---------------+---------------+

```
|               |               |               |               |
|    HopLimit   |    Reserved   |     Flags     |  HeaderLength |
|               |               |               |               |
```

/                       PathSteering TLV                        /
/                                                               /
+---------------+---------------+---------------+---------------+
```
|               Traceroute Request Message TLVs                 |
```

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 assigned in the Packet Type IANA Registry for CCNx (see section 4.1 of [CCNMessages].

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 [PATHSTEERING].


### Path Steering TLV

The message of a traceroute request is presented below:

<table>
<thead>
<tr>
<th>PathSteering_Type</th>
<th>PathSteering_Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 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 is 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:

<table>
<thead>
<tr>
<th>Version</th>
<th>TrReply</th>
<th>PacketLength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserved</td>
<td>Flags</td>
<td>HeaderLength</td>
</tr>
</tbody>
</table>

PathSteering TLV

Traceroute Reply Message TLVs

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 assigned in the Packet Type IANA Registry for CCNx (see section 4.1 of [CCNMessages]).

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 returned from network caches.

```
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+---------------+---------------+---------------+---------------+
|                               |                               |
+---------------+---------------+---------------+---------------+
|        MessageType = 2        |          MessageLength        |
+---------------+---------------+---------------+---------------+
|                               |                               |
+---------------+---------------+---------------+---------------+
|                            Name TLV                           |
+---------------+---------------+---------------+---------------+
|                                                               |
+---------------+---------------+---------------+---------------+
|                         PayloadType TLV                       |
+---------------+---------------+---------------+---------------+
|                                                               |
+---------------+---------------+---------------+---------------+
|                         ExpiryTime TLV                        |
+---------------+---------------+---------------+---------------+
```

**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 or by employing a more comprehensive management tool such as CCNInfo [CCNInfo] 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 Hop limit reached the 0 value.
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
                   Parameters?
```

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.

The "Parameters" field of the Request contains the following PathSteering TLV:

```
PathSteering TLV ::= PATHSTEERING-TLV-TYPE TLV-LENGTH BYTE(8)
```

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 with a freshness period that has expired [REALTIME].

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
```

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
```

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 is 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) is extracted.

If the HopLimit has not expired (its value is greater than 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 indicating "No Route" in the case of CCNx or a network NACK in the case of NDN is sent downstream.

If the HopLimit value is equal to zero, the forwarder generates a traceroute reply. This reply includes the forwarder’s administrative 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 corresponding TrReply Code TLV.

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

- If 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 is set to indicate the specific condition that was met. If none of those conditions was met, the TrReply Code is set to 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 allows 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 depends on various network design factors 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 border 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 traceroute requests expressed by the client. In this way, a request will be forwarded based on the routable part of its name. When it reaches the network region where the original locally-scoped name is routable, the border forwarder rewrites the request name and deletes 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 border forwarder has also to rewrite the name of a reply and prepend the routable prefix of the corresponding request.
8. Security Considerations

A reflection attack could occur in the case of a traceroute reply with the CCNx packet format if a compromised forwarder includes in the reply the name of a victim forwarder. This could redirect the future administrative traffic towards the victim. To foil such reflection attacks, the forwarder that generates a traceroute reply must sign the name included in the payload. In this way, the client is able to verify that the included name is legitimate and refers to the forwarder that generated the reply. Alternatively, the forwarder could include in the reply payload their routable prefix(es) encoded as a signed NDN Link Object [SNAMP].

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 foil 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 therefore is thereby separated from load on the forwarder itself. 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 border 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 also note that traceroute requests have the same privacy characteristics as regular Interests.

9. References
9.1. Normative References


9.2. Informative References


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 not wish 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.

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