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When to use RFC 6553, 6554 and IPv6-in-IPv6
draft-ietf-roll-useofrplinfo-08

Abstract

   This document looks at different data flows through LLN (Low-Power
   and Lossy Networks) where RPL (IPv6 Routing Protocol for Low-Power
   and Lossy Networks) is used to establish routing. The document
   enumerates the cases where RFC 6553, RFC 6554 and IPv6-in-IPv6
   encapsulation is required. This analysis provides the basis on which
   to design efficient compression of these headers.

Status of This Memo

   This Internet-Draft is submitted in full conformance with the
   provisions of BCP 78 and BCP 79.

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   time. It is inappropriate to use Internet-Drafts as reference
   material or to cite them other than as "work in progress."

   This Internet-Draft will expire on March 17, 2017.

Table of Contents

1. Introduction

   RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks)
   [RFC6550] is a routing protocol for constrained networks. RFC 6553
   [RFC6553] defines the "RPL option" (RPI), carried within the IPv6
   Hop-by-Hop header to quickly identify inconsistencies (loops) in the
   routing topology. RFC 6554 [RFC6554] defines the "RPL Source Route
   Header" (RH3), an IPv6 Extension Header to deliver datagrams within a
   RPL routing domain, particularly in non-storing mode.

   These various items are referred to as RPL artifacts, and they are
   seen on all of the data-plane traffic that occurs in RPL routed
   networks; they do not in general appear on the RPL control plane
   traffic at all which is mostly hop-by-hop traffic (one exception
   being DAO messages in non-storing mode).

   It has become clear from attempts to do multi-vendor
   interoperability, and from a desire to compress as many of the above
   artifacts as possible that not all implementors agree when artifacts
   are necessary, or when they can be safely omitted, or removed.

   An interim meeting went through the 24 cases defined here to discover
   if there were any shortcuts, and this document is the result of that
   discussion. This document should not be defining anything new, but
   it may clarify what is correct and incorrect behaviour.

   The related document A Routing Header Dispatch for 6LoWPAN (6LoRH)
   [I-D.ietf-roll-routing-dispatch] defines a method to compress RPL
   Option information and Routing Header type 3 [RFC6554], an efficient
   IP-in-IP technique, and use cases proposed for the
   [Second6TischPlugtest] involving 6loRH.

2. Terminology and Requirements Language

   The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
   "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this
   document are to be interpreted as described in RFC 2119 [RFC2119].

   Terminology defined in [RFC7102] applies to this document: LBR, LLN,
   RPL, RPL Domain and ROLL.

   RPL-node: It is device which implements RPL, thus we can say that the
   device is RPL-capable or RPL-aware. Please note that the device can

be found inside the LLN or outside LLN. In this document a RPL-node
which is a leaf is called RPL-aware-leaf.

RPL-not-capable: It is device which do not implement RPL, thus we can
say that the device is not-RPL-aware. Please note that the device
can be found inside the LLN. In this document a not-RPL-node which
is a leaf is called not-RPL-aware-leaf.

2.1. hop-by-hop IPv6-in-IPv6 headers

The term "hop-by-hop IPv6-in-IPv6" header refers to: adding a header
that originates from a node to an adjacent node, using the addresses
(usually the GUA or ULA, but could use the link-local addresses) of
each node. If the packet must traverse multiple hops, then it must
be decapsulated at each hop, and then re-encapsulated again in a
similar fashion.

3. Sample/reference topology

A RPL network is composed of a 6LBR (6LoWPAN Border Router), Backbone
Router (6BBR), 6LR (6LoWPAN Router) and 6LN (6LoWPAN Node) as leaf
logically organized in a DODAG structure (Destination Oriented
Directed Acyclic Graph).

RPL defines the RPL Control messages (control plane), a new ICMPv6
[RFC4443] message with Type 155. DIS (DODAG Information
Solicitation), DIO (DODAG Information Object) and DAO (Destination
Advertisement Object) messages are all RPL Control messages but with
different Code values. A RPL Stack is showed in Figure 1.

RPL supports two modes of Downward traffic: in storing mode (RPL-SM),
it is fully stateful or an in non-storing (RPL-NSM), it is fully
source routed. A RPL Instance is either fully storing or fully non-
storing, i.e. a RPL Instance with a combination of storing and non-
storing nodes is not supported with the current specifications at the
time of writing this document.

```
+--------------+
| Upper Layers |
|              |
+--------------+
|    RPL       |
|              |
+--------------+
|    ICMPv6    |
|              |
+--------------+
|    IPv6      |
|              |
+--------------+
|    6LoWPAN   |
|              |
+--------------+
|    PHY-MAC   |
|              |
+--------------+
```

Figure 1: RPL Stack.

```
                                 +---------+
                            +---+Internet |
                            |   +---------+
                            |
                     +----+--+
                     | DODAG |  node:01
              +---------+ Root  +----------+
              |         | 6LBR  |          |
              |         +----+--+          |
              |            |               |
              |            |               |
             ...          ...             ...
              |            |               |
          +-----+-+    +--+---+        +--+---+
          |6LR    |    |      |        |      |
      +-----+     |    |      |        |      |
      |     |  11 |    |  12  |        |  13 +------+
      |     +-----+-+  +-+----+        +-+----+     |
      |          |       |               |         |
      |          |       |               |         |
      | 21       | 22    | 23            | 24      | 25
     +-+---+    +-+---+  +--+--+        +- --+    +---+-+
     |Leaf |    |     |  |     |        |Leaf|    |Leaf |
     | 6LN |    |     |  |     |        | 6LN|    | 6LN |
     +-----+    +-----+  +-----+        +----+    +-----+
```
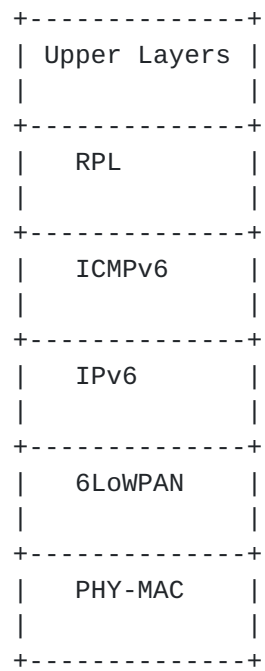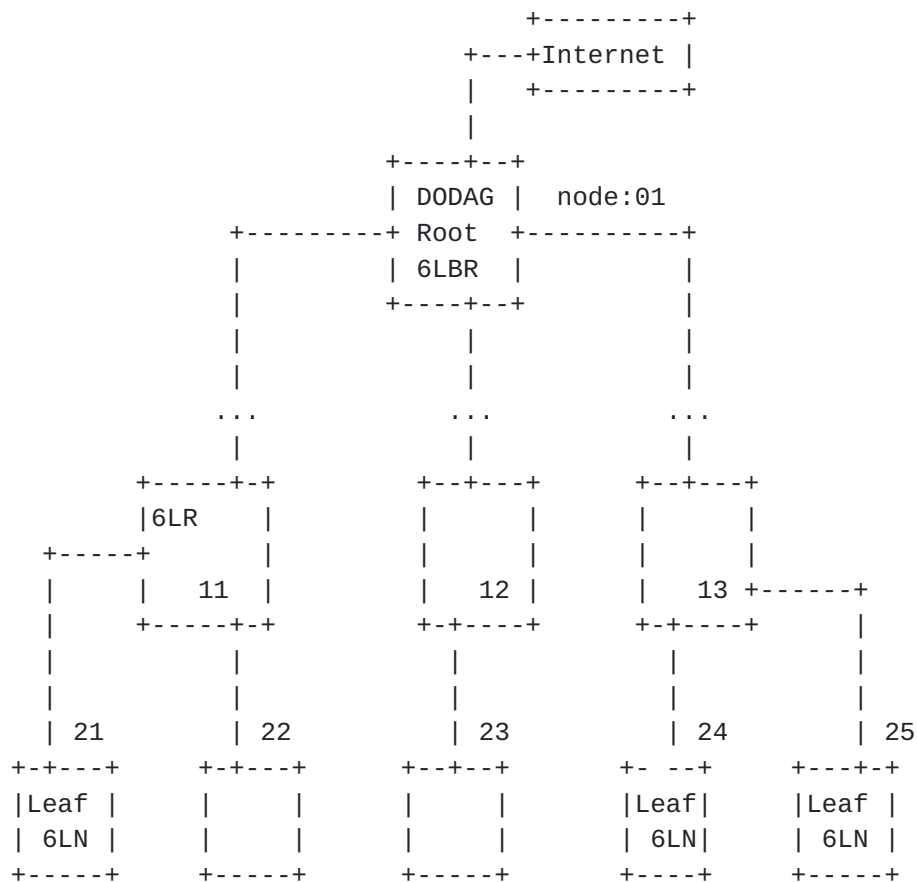
Figure 2: A reference RPL Topology.

In Figure 2 is showed the reference RPL Topology for this document.
The numbers in or above the nodes are there so that they may be
referenced in subsequent sections. In the figure, a 6LN can be a
router or a host. The 6LN leafs marked as (21) is a RPL host that
does not have forwarding capability and (25) is a RPL router. The
leaf marked 6LN (24) is a device which does not speak RPL at all
(not-RPL-aware), but uses Router-Advertisements, 6LowPAN DAR/DAC and
efficient-ND only to participate in the network [RFC6775]. In the
document this leaf (24) is often named IPv6 node. The 6LBR in the
figure is the root of the Global DODAG.

This document is in part motivated by the work that is ongoing at the
6TiSCH working group. The 6TiSCH architecture
[I-D.ietf-6tisch-architecture] draft explains the network
architecture of a 6TiSCH network.

[4](#). Use cases

In data plane context a combination of [RFC6553](#), [RFC6554](#) and IPv6-in-IPv6 encapsulation is going to be analyzed for the following traffic flows.

This version of the document assumes the changes in [I-D.ietf-6man-rfc2460bis] are passed (at the time to write this specification, the draft is on version 05).

RPL-aware-leaf to root

root to RPL-aware-leaf

not-RPL-aware-leaf to root

root to not-RPL-aware-leaf

RPL-aware-leaf to Internet

Internet to RPL-aware-leaf

not-RPL-aware-leaf to Internet

Internet to not-RPL-aware-leaf

RPL-aware-leaf to RPL-aware-leaf (storing and non-storing)

RPL-aware-leaf to not-RPL-aware-leaf (non-storing)

not-RPL-aware-leaf to RPL-aware-leaf (storing and non-storing)

not-RPL-aware-leaf to not-RPL-aware-leaf (non-storing)

This document assumes the rule that a Header cannot be inserted or removed on the fly inside an IPv6 packet that is being routed. This is a fundamental precept of the IPv6 architecture as outlined in [RFC2460]. Extensions may not be added or removed except by the sender or the receiver.

But, options in the Hop-by-Hop option which are marked with option type 01 ([RFC2460] section 4.2 and [I-D.ietf-6man-rfc2460bis]) SHOULD be ignored when received by a host or router which does not understand that option.

This means that in general, any packet that leaves the RPL domain of an LLN (or leaves the LLN entirely) will NOT be discarded, when it

has the [RFC6553] RPL Option Header known as the RPI or [RFC6554]
SRH3 Extension Header (S)RH3.

The recent change to the second of these rules it means that the RPI
Hop-by-Hop option MAY be left in place even if the end host does not
understand it.

NOTE: There is some possible security risk when the RPI information
is released to the Internet. At this point this is a theoretical
situation. It is clear that the RPI option would waste some network
bandwidth when it escapes.

An intermediate router that needs to add an extension header (SHR3 or
RPI Option) must encapsulate the packet in an (additional) outer IP
header. The new header can be placed is placed after this new outer
IP header.

A corollory is that an SHR3 or RPI Option can only be removed by an
intermediate router if it is placed in an encapsulating IPv6 Header,
which is addressed to the intermediate router. When it does so, the
whole encapsulating header must be removed. (A replacement may be
added). This sometimes can result in outer IP headers being
addressed to the next hop router using link-local addresses.

Both RPI and RH3 headers may be modified in very specific ways by
routers on the path of the packet without the need to add to remove
an encapsulating header. Both headers were designed with this
modification in mind, and both the RPL RH and the RPL option are
marked mutable but recoverable: so an IPsec AH security header can be
applied across these headers, but it can not secure the values which
mutate.

RPI should be present in every single RPL data packet. There is one
exception in non-storing mode: when a packet is going down from the
root. In a downward non-storing mode, the entire route is written,
so there can be no loops by construction, nor any confusion about
which forwarding table to use (as the root has already made all
routing decisions). There still may be cases (such as in 6tisch)
where the instanceID portion of the RPI header may still be needed to
pick an appropriate priority or channel at each hop.

In the tables present in this document, the term "RPL aware leaf" is
has been shortened to "Raf", and "not-RPL aware leaf" has been
shortened to "~Raf" to make the table fit in available space.

The earlier examples are more extensive to make sure that the process
is clear, while later examples are more consise.

5. Storing mode

   In storing mode (fully stateful), the sender cannot determine whether
   the destination is RPL-capable and thus would need an IP-in-IP
   header. The IP-in-IP header needs to be addressed on a hop-by-hop
   basis so that the last 6LR can remove the RPI header. Additionally,
   The sender can determine if the destination is inside the LLN by
   looking if the destination address is matched by the DIO's PIO
   option.

   The following table summarizes what headers are needed in the
   following scenarios, and indicates when the IP-in-IP header must be
   inserted on a hop-by-hop basis, and when it can target the
   destination node directly. There are three possible situations: hop-
   by-hop necessary (indicated by "hop"), or destination address
   possible (indicated by "dst"). In all cases hop by hop can be used.
   In cases where no IP-in-IP header is needed, the column is left
   blank.

   The leaf can be a router 6LR or a host, both indicated as 6LN.

Use Case	RPI	RH3	IP-in-IP	IP-in-IP dst
Raf to root	Yes	No	No	--
root to Raf	Yes	No	No	--
root to ~Raf	Yes	No	No	--
~Raf to root	Yes	No	Yes	root
Raf to Int	Yes	No	No	--
Int to Raf	Yes	No	Yes	raf
~Raf to Int	Yes	No	Yes	root
Int to ~Raf	Yes	No	Yes	hop
Raf to Raf	Yes	No	No	--
Raf to ~Raf	Yes	No	No	--
~Raf to Raf	Yes	No	Yes	dst
~Raf to ~Raf	Yes	No	Yes	hop

                 Table 1: Headers needed in Storing mode: RPI, RH3, IP-in-IP
                                    encapsulation

5.1. Example of Flow from RPL-aware-leaf to root

   In storing mode, RFC 6553 (RPI) is used to send RPL Information
   instanceID and rank information.

   As stated in Section 16.2 of [RFC6550] a RPL-aware-leaf node does
   not generally issue DIO messages; a leaf node accepts DIO messages

from upstream.   (When the inconsistency in routing occurs, a leaf
node will generate a DIO with an infinite rank, to fix it).   It may
issue DAO and DIS messages though it generally ignores DAO and DIS
messages.

In this case the flow comprises:

RPL-aware-leaf (6LN) --> 6LR1,... --> 6LRN --> root (6LBR)

As it was mentioned In this document 6LRs, 6LBR are always full-
fledge RPL routers.

The 6LN inserts the RPI header, and sends the packet to 6LR which
decrements the rank in RPI and sends the packet up.   When the packet
arrives at 6LBR, the RPI is removed and the packet is processed.

No IP-in-IP header is required.

The RPI header can be removed by the 6LBR because the packet is
addressed to the 6LBR.   The 6LN must know that it is communicating
with the 6LBR to make use of this scenario.   The 6LN can know the
address of the 6LBR because it knows the address of the root via the
DODAGID in the DIO messages.

```
+-------------------+-----+------+------+
| Header            | 6LN | 6LR  | 6LBR |
+-------------------+-----+------+------+
| Inserted headers  | RPI | --   | --   |
| Removed headers   | --  | --   | RPI  |
| Re-added headers  | --  | --   | --   |
| Modified headers  | --  | RPI  | --   |
| Untouched headers | --  | --   | --   |
+-------------------+-----+------+------+
```

 Storing: Summary of the use of headers from RPL-aware-leaf to root

5.2. Example of Flow from root to RPL-aware-leaf

In this case the flow comprises:

root (6LBR) --> 6LR1,... --> 6LRN --> RPL-aware-leaf (6LN)

In this case the 6LBR inserts RPI header and sends the packet down,
the 6LR is going to increment the rank in RPI (examines instanceID
for multiple tables), the packet is processed in 6LN and RPI removed.

No IP-in-IP header is required.

```
            +-------------------+------+-------+------+
            | Header            | 6LBR | 6LR   | 6LN  |
            +-------------------+------+-------+------+
            | Inserted headers  | RPI  | --    | --   |
            | Removed headers   | --   | --    | RPI  |
            | Re-added headers  | --   | --    | --   |
            | Modified headers  | --   | RPI   | --   |
            | Untouched headers | --   | --    | --   |
            +-------------------+------+-------+------+
```

   Storing: Summary of the use of headers from root to RPL-aware-leaf

5.3. Example of Flow from root to not-RPL-aware-leaf

   In this case the flow comprises:

   root (6LBR) --> 6LR1,... --> 6LRN --> not-RPL-aware-leaf (IPv6)

   As the RPI extension can be ignored by the not-RPL-aware leaf, this
   situation is identical to the previous scenario.

```
        +-------------------+------+----------+----------------+
        | Header            | 6LBR | 6LR(1..N) | 6LN           |
        +-------------------+------+----------+----------------+
        | Inserted headers  | RPI  | --        | --            |
        | Removed headers   | --   | --        | --            |
        | Re-added headers  | --   | --        | --            |
        | Modified headers  | --   | RPI       | --            |
        | Untouched headers | --   | --        | RPI (Ignored) |
        +-------------------+------+----------+----------------+
```

    Storing: Summary of the use of headers from root to not-RPL-aware-
                                  leaf

5.4. Example of Flow from not-RPL-aware-leaf to root

   In this case the flow comprises:

   not-RPL-aware-leaf (IPv6) --> 6LR1,... --> 6LRN --> root (6LBR)

   When the packet arrives from IPv6 node to 6LR, the 6LR1 will insert
   an RPI header, encapsuladed in a IPv6-in-IPv6 header. The IPv6-in-
   IPv6 header can be addressed to the next hop, or to the root. The
   root removes the header and processes the packet.

```
+-----------+------+--------------+--------------+--------------+
| Header    | IPv6 | 6LR1         | 6LRN         | 6LBR         |
+-----------+------+--------------+--------------+--------------+
| Inserted  | --   | IP-in-IP(RPI)| --           | --           |
| headers   |      |              |              |              |
| Removed   | --   | --           | --           | IP-in-IP(RPI)|
| headers   |      |              |              |              |
| Re-added  | --   | --           | --           | --           |
| headers   |      |              |              |              |
| Modified  | --   | --           | IP-in-IP(RPI)| --           |
| headers   |      |              |              |              |
| Untouched | --   | --           | --           | --           |
| headers   |      |              |              |              |
+-----------+------+--------------+--------------+--------------+
```

Storing: Summary of the use of headers from not-RPL-aware-leaf to root

5.5. Example of Flow from RPL-aware-leaf to Internet

RPL information from RFC 6553 MAY go out to Internet as it will be ignored by nodes which have not been configured to be RPI aware.

In this case the flow comprises:

RPL-aware-leaf (6LN) --> 6LR1,... --> 6LRN --> root (6LBR) --> Internet

No IP-in-IP header is required.

```
+-------------------+------+-----------+------+---------------+
| Header            | 6LN  | 6LR(1..N) | 6LBR | Internet      |
+-------------------+------+-----------+------+---------------+
| Inserted headers  | RPI  | --        | --   | --            |
| Removed headers   | --   | --        | --   | --            |
| Re-added headers  | --   | --        | --   | --            |
| Modified headers  | --   | RPI       | --   | --            |
| Untouched headers | --   | --        | --   | RPI (Ignored) |
+-------------------+------+-----------+------+---------------+
```

Storing: Summary of the use of headers from RPL-aware-leaf to Internet

5.6. Example of Flow from Internet to RPL-aware-leaf

In this case the flow comprises:

Internet --> root (6LBR) --> 6LR1,... --> 6LRN --> RPL-aware-leaf
(6LN)

When the packet arrives from Internet to 6LBR the RPI header is added
in a outer IPv6-in-IPv6 header and sent to 6LR, which modifies the
rank in the RPI. When the packet arrives at 6LN the RPI header is
removed and the packet processed.

```
+----------+--------+-------------+--------------+--------------+
| Header   | Interne | 6LBR        | 6LR(1...N)   | 6LN          |
|          | t       |             |              |              |
+----------+--------+-------------+--------------+--------------+
| Inserted | --     | IP-in-      | --           | --           |
| headers  |        | IP(RPI)     |              |              |
| Removed  | --     | --          | --           | IP-in-IP(RPI) |
| headers  |        |             |              |              |
| Re-added | --     | --          | --           | --           |
| headers  |        |             |              |              |
| Modified | --     | --          | IP-in-IP(RPI) | --          |
| headers  |        |             |              |              |
| Untouche | --     | --          | --           | --           |
| d        |        |             |              |              |
| headers  |        |             |              |              |
+----------+--------+-------------+--------------+--------------+
```

            Storing: Summary of the use of headers from Internet to RPL-aware-
                                    leaf

5.7. Example of Flow from not-RPL-aware-leaf to Internet

In this case the flow comprises:

not-RPL-aware-leaf (IPv6) --> 6LR1,... --> 6LRN --> root (6LBR) -->
Internet

The 6LR1 node will add an IP-in-IP(RPI) header addressed either to
the root, or hop-by-hop such that the root can remove the RPI header
before passing upwards.

The originating node will ideally leave the IPv6 flow label as zero
so that it can be better compressed through the LLN, and the 6LBR
will set the flow label to a non-zero value when sending to the
Internet.

```
+---------+-----+------------+------------+------------+---------+
| Header  | IPv | 6LR1       | 6LBN       | 6LBR       | Interne |
|         | 6   |            |            |            | t       |
+---------+-----+------------+------------+------------+---------+
| Inserte | --  | IP-in-     | --         | --         | --      |
| d       |     | IP(RPI)    |            |            |         |
| headers |     |            |            |            |         |
| Removed | --  | --         | --         | IP-in-     | --      |
| headers |     |            |            | IP(RPI)    |         |
| Re-     | --  | --         | --         | --         | --      |
| added   |     |            |            |            |         |
| headers |     |            |            |            |         |
| Modifie | --  | --         | IP-in-     | --         | --      |
| d       |     |            | IP(RPI)    |            |         |
| headers |     |            |            |            |         |
| Untouch | --  | --         | --         | --         | --      |
| ed      |     |            |            |            |         |
| headers |     |            |            |            |         |
+---------+-----+------------+------------+------------+---------+
```

Storing: Summary of the use of headers from not-RPL-aware-leaf to
Internet

5.8. Example of Flow from Internet to non-RPL-aware-leaf

In this case the flow comprises:

Internet --> root (6LBR) --> 6LR1,... --> 6LRN --> not-RPL-aware-leaf
(IPv6)

The 6LBR will have to add an RPI header within an IP-in-IP header.
The IP-in-IP can be addressed to the not-RPL-aware-leaf, leaving the
RPI inside.

The 6LBR MAY set the flow label on the inner IP-in-IP header to zero
in order to aid in compression, as the packet will not emerge again
from the LLN.

```
+-----------+----------+--------------+--------------+------------+
| Header    | Internet | 6LBR         | 6LR(1...N)   | IPv6       |
+-----------+----------+--------------+--------------+------------+
| Inserted  | --       | IP-in-IP(RPI)| --           | --         |
| headers   |          |              |              |            |
| Removed   | --       | --           | IP-in-IP(RPI)| --         |
| headers   |          |              |              |            |
| Re-added  | --       | --           | --           | --         |
| headers   |          |              |              |            |
| Modified  | --       | --           | IP-in-IP(RPI)| --         |
| headers   |          |              |              |            |
| Untouched | --       | --           | --           | RPI        |
| headers   |          |              |              | (Ignored)  |
+-----------+----------+--------------+--------------+------------+
```

   Storing: Summary of the use of headers from Internet to non-RPL-
                             aware-leaf

5.9. Example of Flow from RPL-aware-leaf to RPL-aware-leaf

   In [RFC6550] RPL allows a simple one-hop optimization for both
   storing and non-storing networks. A node may send a packet destined
   to a one-hop neighbor directly to that node. Section 9 in [RFC6550].

   In this case the flow comprises:

   6LN --> 6LR1 --> common parent (6LRx) --> 6LRN --> 6LN

   This case is assumed in the same RPL Domain. In the common parent,
   the direction of RPI is changed (from increasing to decreasing the
   rank).

   While the 6LR nodes will update the RPI, no node needs to add or
   remove the RPI, so no IP-in-IP headers are necessary. This may be
   done regardless of where the destination is, as the included RPI will
   be ignored by the receiver.

Header	6LN src	6LR1	6LRx (common parent)	6LRN	6LN dst
Inserted headers	RPI	--	--	--	--
Removed headers	--	--	--	--	RPI
Re-added headers	--	--	--	--	--
Modified headers	--	RPI (decreasing rank)	RPI (increasing rank)	--	--
Untouched headers	--	--	--	--	--

Storing: Summary of the use of headers for RPL-aware-leaf to RPL-aware-leaf

5.10. Example of Flow from RPL-aware-leaf to non-RPL-aware-leaf

In this case the flow comprises:

6LN --> 6LR1 --> common parent (6LRx) --> 6LRN --> not-RPL-aware 6LN
(IPv6)

This situation is identical to the previous situation Section 5.9

```
+-----------+-----+------------+------------+------+-------------+
| Header    | 6LN | 6LR1       | 6LRx       | 6LRN | IPv6        |
|           | src |            | (common    |      |             |
|           |     |            | parent)    |      |             |
+-----------+-----+------------+------------+------+-------------+
| Inserted  | RPI | --         | --         | --   | --          |
| headers   |     |            |            |      |             |
| Removed   | --  | --         | --         | --   | RPI         |
| headers   |     |            |            |      |             |
| Re-added  | --  | --         | --         | --   | --          |
| headers   |     |            |            |      |             |
| Modified  | --  | RPI        | RPI        | --   | --          |
| headers   |     | (decreasing| (increasing|      |             |
|           |     | rank)      | rank)      |      |             |
| Untouched | --  | --         | --         | --   | RPI(Ignored)|
| headers   |     |            |            |      |             |
+-----------+-----+------------+------------+------+-------------+
```

Storing: Summary of the use of headers for RPL-aware-leaf to RPL-
aware-leaf

5.11. Example of Flow from not-RPL-aware-leaf to RPL-aware-leaf

In this case the flow comprises:

not-RPL-aware 6LN (IPv6) --> 6LR1 --> common parent (6LRx) --> 6LRN
--> 6LN

The 6LR1 receives the packet from the the IPv6 node and inserts and
the RPI header encapsulated in IPv6-in-IPv6 header. The IP-in-IP
header is addressed to the destination 6LN.

Header	IPv6	6LR1	common parent (6LRx)	6LRn	6LN
Inserted headers	--	IP-in-IP(RPI)	--	--	--
Removed headers	--	--	--	--	IP-in-IP(RPI)
Re-added headers	--	--	--	--	--
Modified headers	--	--	IP-in-IP(RPI)	IP-in-IP(RPI)	--
Untouched headers	--	--	--	--	--

Storing: Summary of the use of headers from not-RPL-aware-leaf to
RPL-aware-leaf

5.12. Example of Flow from not-RPL-aware-leaf to not-RPL-aware-leaf

In this case the flow comprises:

not-RPL-aware 6LN (IPv6 src)--> 6LR1 --> 6LR2 --> root (6LBR) -->
6LRn --> not-RPL-aware 6LN (IPv6 dst)

This flow is identical to Section 5.11

The 6LR receives the packet from the the IPv6 node and inserts the
RPI header (RPIa) encapsulated in IPv6-in-IPv6 header. The IPv6-in-
IPv6 header is addressed to the 6LBR. The 6LBR remove the IPv6-in-
IPv6 header and insert another one (RPIb) with destination to 6LRn
node.

Header	IPv6 src	6LR1	6LR2	6LBR	6LRn	IPv6 dst
Inserted headers	--	IP-in-IP(RPIa)	--	IP-in-IP(RPIb)	--	--
Removed headers	--	--	--	--	--	--
Re-added headers	--	--	--	--	IP-in-IP(RPIb)	--
Modified headers	--	--	IP-in-IP(RPIa)	--	IP-in-IP(RPIb)	--
Untouched headers	--	--	--	--	--	--

               Storing: Summary of the use of headers from not-RPL-aware-leaf to
                              non-RPL-aware-leaf

6. Non Storing mode

```
+--------------+------+------+-----------+---------------+
| Use Case     | RPI  | RH3  | IP-in-IP  | IP-in-IP dst  |
+--------------+------+------+-----------+---------------+
| Raf to root  | Yes  | No   | No        | --            |
| root to Raf  | Opt  | Yes  | No        | --            |
| root to ~Raf | No   | Yes  | Yes       | 6LR           |
| ~Raf to root | Yes  | No   | Yes       | root          |
| Raf to Int   | Yes  | No   | Yes       | root          |
| Int to Raf   | Opt  | Yes  | Yes       | dst           |
| ~Raf to Int  | Yes  | No   | Yes       | root          |
| Int to ~Raf  | Opt  | Yes  | Yes       | 6LR           |
| Raf to Raf   | Yes  | Yes  | Yes       | root/dst      |
| Raf to ~Raf  | Yes  | Yes  | Yes       | root/6LR      |
| ~Raf to Raf  | Yes  | Yes  | Yes       | root/6LN      |
| ~Raf to ~Raf | Yes  | Yes  | Yes       | root/6LR      |
+--------------+------+------+-----------+---------------+
```

Table 2: Headers needed in Non-Storing mode: RPI, RH3, IP-in-IP
encapsulation

6.1. Example of Flow from RPL-aware-leaf to root

In non-storing mode the leaf node uses default routing to send
traffic to the root. The RPI header must be included to avoid/detect
loops.

RPL-aware-leaf (6LN) --> 6LR --> root (6LBR)

This situation is the same case as storing mode.

```
+-------------------+-----+------+------+
| Header            | 6LN | 6LR  | 6LBR |
+-------------------+-----+------+------+
| Inserted headers  | RPI | --   | --   |
| Removed headers   | --  | --   | RPI  |
| Re-added headers  | --  | --   | --   |
| Modified headers  | --  | RPI  | --   |
| Untouched headers | --  | --   | --   |
+-------------------+-----+------+------+
```

Non Storing: Summary of the use of headers from RPL-aware-leaf to
root

6.2. Example of Flow from root to RPL-aware-leaf

In this case the flow comprises:

root (6LBR)--> 6LR --> RPL-aware-leaf (6LN)

The 6LBR will insert an RH3, and may optionally insert an RPI header.
No IP-in-IP header is necessary as the traffic originates with an RPL
aware node, the 6LBR. The destination is known to RPL-aware because,
the root knows the whole topology in non-storing mode.

```
+-------------------+-----------------+------+----------+
| Header            | 6LBR            | 6LR  | 6LN      |
+-------------------+-----------------+------+----------+
| Inserted headers  | (opt: RPI), RH3 | --   | --       |
| Removed headers   | --              | --   | RH3,RPI  |
| Re-added headers  | --              | --   | --       |
| Modified headers  | --              | RH3  | --       |
| Untouched headers | --              | --   | --       |
+-------------------+-----------------+------+----------+
```

   Non Storing: Summary of the use of headers from root to RPL-aware-
                              leaf

6.3. Example of Flow from root to not-RPL-aware-leaf

In this case the flow comprises:

root (6LBR)--> 6LR1...-->6LRn --> not-RPL-aware-leaf (IPv6)

In 6LBR the RH3 is added, modified in each intermediate 6LR (6LR1 and
so on) and it is fully consumed in the last 6LR (6LRn), but left
there. If RPI is left present, the IPv6 node which does not
understand it will ignore it (following 2460bis), thus encapsulation
is not necesary. Due the complete knowledge of the topology at the
root, the 6LBR is able to address the IP-in-IP header to the last
6LR.

```
+----------------+-------------+-------------+-------------+------+
| Header         | 6LBR        | 6LR1        | 6LRn        | IPv6 |
+----------------+-------------+-------------+-------------+------+
| Inserted       | (opt: RPI), | --          | --          | --   |
| headers        | RH3         |             |             |      |
| Removed        | --          | RH3         | --          | --   |
| headers        |             |             |             |      |
| Re-added       | --          | --          | --          | --   |
| headers        |             |             |             |      |
| Modified       | --          | (opt: RPI), | (opt: RPI), | --   |
| headers        |             | RH3         | RH3         |      |
| Untouched      | --          | --          | --          | RPI  |
| headers        |             |             |             |      |
+----------------+-------------+-------------+-------------+------+
```

           Non Storing: Summary of the use of headers from root to not-RPL-
                                 aware-leaf

6.4. Example of Flow from not-RPL-aware-leaf to root

   In this case the flow comprises:

   IPv6-node --> 6LR1 ...--> 6LRn --> root (6LBR)

   In this case the RPI is added by the first 6LR (6LR1), encapsulated
   in an IP-in-IP header, and is modified in the followings 6LRs. The
   RPI and entire packet is consumed by the root.

```
+------------+------+--------------+--------------+--------------+
| Header     | IPv6 | 6LR1         | 6LR2         | 6LBR         |
+------------+------+--------------+--------------+--------------+
| Inserted   | --   | IP-in-IP(RPI)| --           | --           |
| headers    |      |              |              |              |
| Removed    | --   | --           | --           | IP-in-IP(RPI)|
| headers    |      |              |              |              |
| Re-added   | --   | --           | --           | --           |
| headers    |      |              |              |              |
| Modified   | --   | IP-in-IP(RPI)| IP-in-IP(RPI)| --           |
| headers    |      |              |              |              |
| Untouched  | --   | --           | --           | --           |
| headers    |      |              |              |              |
+------------+------+--------------+--------------+--------------+
```

           Non Storing: Summary of the use of headers from not-RPL-aware-leaf to
                                   root

6.5. Example of Flow from RPL-aware-leaf to Internet

   In this case the flow comprises:

   RPL-aware-leaf (6LN) --> 6LR1 ...--> 6LRn --> root (6LBR) -->
   Internet

   This case is identical to storing-mode case.

   The IPv6 flow label should be set to zero to aid in compression, and
   the 6LBR will set it to a non-zero value when sending towards the
   Internet.

```
   +-------------------+------+-----------+------+---------------+
   | Header            | 6LN  | 6LR(1..N) | 6LBR | Internet      |
   +-------------------+------+-----------+------+---------------+
   | Inserted headers  | RPI  | --        | --   | --            |
   | Removed headers   | --   | --        | --   | --            |
   | Re-added headers  | --   | --        | --   | --            |
   | Modified headers  | --   | RPI       | --   | --            |
   | Untouched headers | --   | --        | --   | RPI (Ignored) |
   +-------------------+------+-----------+------+---------------+
```

             Non Storing: Summary of the use of headers from RPL-aware-leaf to
                                    Internet

6.6. Example of Flow from Internet to RPL-aware-leaf

   In this case the flow comprises:

   Internet --> root (6LBR) --> 6LR1...--> 6LRn --> RPL-aware-leaf (6LN)

   The 6LBR must add an RH3 header. As the 6LBR will know the path and
   address of the target node, it can address the IP-in-IP header to
   that node. The 6LBR will zero the flow label upon entry in order to
   aid compression.

   The RPI may be added or not, it is optional.

Header	Inter net	6LBR	6LR	6LN
Insert ed hea ders	--	IP-in-IP(RH3,o pt:RPI)	--	--
Remove d head ers	--	--	--	IP-in-IP(RH3,o pt:RPI)
Re- added header s	--	--	--	--
Modifi ed hea ders	--	--	IP-in-IP(RH3,o pt:RPI)	--
Untouc hed he aders	--	--	--	--

Non Storing: Summary of the use of headers from Internet to RPL-
aware-leaf

6.7. Example of Flow from not-RPL-aware-leaf to Internet

In this case the flow comprises:

not-RPL-aware-leaf (IPv6) --> 6LR1..--> 6LRn --> root (6LBR) -->
Internet

In this case the flow label is recommended to be zero in the IPv6
node. As RPL headers are added in the IPv6 node, the first 6LN will
add an RPI header inside a new IP-in-IP header. The IP-in-IP header
will be addressed to the root. This case is identical to the
storing-mode case (Section 5.7).

Header	IPv6	6LR1	6LRn	6LBR	Internet
Inserted headers	--	IP-in-IP(RPI)	--	--	--
Removed headers	--	--	--	IP-in-IP(RPI)	--
Re-added headers	--	--	--	--	--
Modified headers	--	--	IP-in-IP(RPI)	--	--
Untouched headers	--	--	--	--	--

                Non Storing: Summary of the use of headers from not-RPL-aware-leaf to
                                  Internet

6.8. Example of Flow from Internet to non-RPL-aware-leaf

In this case the flow comprises:

Internet --> root (6LBR) --> 6LR1...--> 6LRn --> not-RPL-aware-leaf
(IPv6)

The 6LBR must add an RH3 header inside an IP-in-IP header. The 6LBR
will know the path, and will recognize that the final node is not an
RPL capable node as it will have received the connectivity DAO from
the nearest 6LR. The 6LBR can therefore make the IP-in-IP header
destination be the last 6LR. The 6LBR will set to zero the flow
label upon entry in order to aid compression.

```
+--------+------+----------------+-----------+-----------+------+
| Header | Inter | 6LBR          | 6LR1      | 6LRn      | IPv6 |
|        | net  |                |           |           |      |
+--------+------+----------------+-----------+-----------+------+
| Insert | --   | IP-in-         | --        | --        | --   |
| ed hea |      | IP(RH3,opt:RPI) |          |           |      |
| ders   |      |                |           |           |      |
| Remove | --   | --             | --        | IP-in-    | --   |
| d head |      |                |           | IP(RH3,   |      |
| ers    |      |                |           | RPI)      |      |
| Re-    | --   | --             | --        | --        | --   |
| added  |      |                |           |           |      |
| header |      |                |           |           |      |
| s      |      |                |           |           |      |
| Modifi | --   | --             | IP-in-    | IP-in-    | --   |
| ed hea |      |                | IP(RH3,   | IP(RH3,   |      |
| ders   |      |                | RPI)      | RPI)      |      |
| Untouc | --   | --             | --        | --        | RPI  |
| hed he |      |                |           |           |      |
| aders  |      |                |           |           |      |
+--------+------+----------------+-----------+-----------+------+
```

             NonStoring: Summary of the use of headers from Internet to non-RPL-
                                 aware-leaf

6.9. Example of Flow from RPL-aware-leaf to RPL-aware-leaf

   In this case the flow comprises:

   6LN --> 6LR1 --> root (6LBR) --> 6LRN --> 6LN

   This case involves only nodes in same RPL Domain. The originating
   node will add an RPI header to the original packet, and send the
   packet upwards.

   The originating node SHOULD put the RPI into an IP-in-IP header
   addressed to the root, so that the 6LBR can remove that header. If
   it does not, then additional resources are wasted on the way down to
   carry the useless RPI option.

   The 6LBR will need to insert an RH3 header, which requires that it
   add an IP-in-IP header. It SHOULD be able to remove the RPI, as it
   was contained in an IP-in-IP header addressed to it. Otherwise,
   there MAY be an RPI header buried inside the inner IP header, which
   should get ignored.

Networks that use the RPL P2P extension [RFC6997] are essentially
non-storing DODAGs and fall into this scenario or scenario
Section 6.2, with the originating node acting as 6LBR.

Header	6LN src	6LR1	6LBR	6LRN	6LN dst
Inserted headers	IP-in-IP(RPI1)	--	IP-in-IP(RH3 to 6LN, opt RPI2)	--	--
Removed headers	--	--	IP-in-IP(RPI1)	--	IP-in-IP(RH3, opt RPI2)
Re-added headers	--	--	--	--	--
Modified headers	--	--	--	--	--
Untouched headers	--	--	--	--	--

Non Storing: Summary of the use of headers for RPL-aware-leaf to RPL-
aware-leaf

6.10. Example of Flow from RPL-aware-leaf to not-RPL-aware-leaf

In this case the flow comprises:

6LN --> 6LR1 --> root (6LBR) --> 6LRn --> not-RPL-aware (IPv6)

As in the previous case, the 6LN will insert an RPI (RPI1) header
which MUST be in an IP-in-IP header addressed to the root so that the
6LBR can remove this RPI. The 6LBR will then insert an RH3 inside a
new IP-in-IP header addressed to the 6LN destination node. The RPI
is optional from 6LBR to 6LRn (RPI2).

Header	6LN	6LR1	6LBR	6LRn	IPv6
Inserted headers	IP-in-IP(RPI1)	--	IP-in-IP(RH3, opt RPI2)	--	--
Removed headers	--	--	IP-in-IP(RPI1)	IP-in-IP(RH3, opt RPI2)	--
Re-added headers	--	--	--	--	--
Modified headers	--	IP-in-IP(RPI1)	--	IP-in-IP(RH3, opt RPI2)	--
Untouched headers	--	--	--	--	opt RPI2

Non Storing: Summary of the use of headers from RPL-aware-leaf to
                       not-RPL-aware-leaf

6.11. Example of Flow from not-RPL-aware-leaf to RPL-aware-leaf

In this case the flow comprises:

not-RPL-aware 6LN (IPv6) --> 6LR1 --> root (6LBR) --> 6LRn --> 6LN

This scenario is mostly identical to the previous one. The RPI is
added by the first 6LR (6LR1) inside an IP-in-IP header addressed to
the root. The 6LBR will remove this RPI, and add it's own IP-in-IP
header containing an RH3 header and optional RPI (RPI2).

```
+--------+-----+-----------+------------+-----------+------------+
| Header | IPv | 6LR1      | 6LBR       | 6LRn      | 6LN        |
|        | 6   |           |            |           |            |
+--------+-----+-----------+------------+-----------+------------+
| Insert | --  | IP-in-    | IP-in-     | --        | --         |
| ed hea |     | IP(RPI1)  | IP(RH3, opt|           |            |
| ders   |     |           | RPI2)      |           |            |
| Remove | --  | --        | IP-in-     | --        | IP-in-     |
| d head |     |           | IP(RPI1)   |           | IP(RH3,    |
| ers    |     |           |            |           | opt RPI2)  |
| Re-    | --  | --        | --         | --        | --         |
| added  |     |           |            |           |            |
| header |     |           |            |           |            |
| s      |     |           |            |           |            |
| Modifi | --  | --        | --         | IP-in-    | --         |
| ed hea |     |           |            | IP(RH3,   |            |
| ders   |     |           |            | opt RPI2) |            |
| Untouc | --  | --        | --         | --        | --         |
| hed he |     |           |            |           |            |
| aders  |     |           |            |           |            |
+--------+-----+-----------+------------+-----------+------------+
```

         Non Storing: Summary of the use of headers from not-RPL-aware-leaf to
                              RPL-aware-leaf

6.12. Example of Flow from not-RPL-aware-leaf to not-RPL-aware-leaf

   In this case the flow comprises:

   not-RPL-aware 6LN (IPv6 src)--> 6LR1 --> root (6LBR) --> 6LRn -->
   not-RPL-aware (IPv6 dst)

   This scenario is the combination of the previous two cases.

```
+---------+-----+-------------+-------------+-------------+------+
| Header  | IPv | 6LR1        | 6LBR        | 6LRn        | IPv6 |
|         | 6   |             |             |             | dst  |
|         | src |             |             |             |      |
+---------+-----+-------------+-------------+-------------+------+
| Inserte | --  | IP-in-      | IP-in-      | --          | --   |
| d       |     | IP(RPI1)    | IP(RH3)     |             |      |
| headers |     |             |             |             |      |
| Removed | --  | --          | IP-in-      | IP-in-      | --   |
| headers |     |             | IP(RPI1)    | IP(RH3, opt |      |
|         |     |             |             | RPI2)       |      |
| Re-     | --  | --          | --          | --          | --   |
| added   |     |             |             |             |      |
| headers |     |             |             |             |      |
| Modifie | --  | --          | --          | --          | --   |
| d       |     |             |             |             |      |
| headers |     |             |             |             |      |
| Untouch | --  | --          | --          | --          | --   |
| ed      |     |             |             |             |      |
| headers |     |             |             |             |      |
+---------+-----+-------------+-------------+-------------+------+
```

     Non Storing: Summary of the use of headers from not-RPL-aware-leaf to
                          not-RPL-aware-leaf

7. Observations about the cases

7.1. Storing mode

   [I-D.ietf-roll-routing-dispatch] shows that this hop-by-hop IP-in-IP
   header can be compressed down to {TBD} bytes.

   There are potential significant advantages to having a single code
   path that always processes IP-in-IP headers with no options.

   Thanks to the relaxation of the RFC2406 rule about discarding unknown
   Hop-by-Hop options, there is no longer any uncertainty about when to
   use an IPIP header in the storing mode case. The RPI header SHOULD
   always be added when 6LRs originate packets (without IPIP headers),
   and IPIP headers should always be added (addressed to the root when
   on the way up, to the end-host when on the way down) when a 6LR finds
   it needs to insert an RPI header. (XXX - this is a problem for
   storing mode optimization)

   In order to support the above two cases with full generality, the
   different situations (always do IP-in-IP vs never use IP-in-IP)
   should be signaled in the RPL protocol itself.

7.2. Non-Storing mode

   In the non-storing case, dealing with non-RPL aware leaf nodes is
   much easier as the 6LBR (DODAG root) has complete knowledge about the
   connectivity of all DODAG nodes, and all traffic flows through the
   root node.

   The 6LBR can recognize non-RPL aware leaf nodes because it will
   receive a DAO about that node from the 6LN immediately above that
   node. This means that the non-storing mode case can avoid ever using
   hop-by-hop IP-in-IP headers.

   [I-D.ietf-roll-routing-dispatch] shows how the destination=root, and
   destination=6LN IP-in-IP header can be compressed down to {TBD}
   bytes.

   Unlike in the storing mode case, there is no need for all nodes to
   know about the existence of non-RPL aware nodes. Only the 6LBR needs
   to change when there are non-RPL aware nodes. Further, in the non-
   storing case, the 6LBR is informed by the DAOs when there are non-RPL
   aware nodes.

8. 6LoRH Compression cases

   The [I-D.ietf-roll-routing-dispatch] proposes a compression method
   for RPI, RH3 and IPv6-in-IPv6.

   In Storing Mode, for the examples of Flow from RPL-aware-leaf to non-
   RPL-aware-leaf and non-RPL-aware-leaf to non-RPL-aware-leaf comprise
   an IP-in-IP and RPI compression headers. The type of this case is
   critical since IP-in-IP is encapsulating a RPI header.

```
+--+-----+---+-------------+----------+------------+-------------+
|1 | 0|0 |TSE| 6LoRH Type 6 | Hop Limit | RPI - 6LoRH | LOWPAN IPHC |
+--+-----+---+-------------+----------+------------+-------------+
```

                    Figure 3: Critical IP-in-IP (RPI).

9. IANA Considerations

   There are no IANA considerations related to this document.

10. Security Considerations

The security considerations covering of [RFC6553] and [RFC6554] apply
when the packets get into RPL Domain.

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              archive/web/6tisch/current/pdfgDMQcdCkRz.pdf>.

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