       Asymmetric AODV-P2P-RPL in Low-Power and Lossy Networks (LLNs)
                       draft-ietf-roll-aodv-rpl-05

Abstract

   Route discovery for symmetric and asymmetric Point-to-Point (P2P)
   traffic flows is a desirable feature in Low power and Lossy Networks
   (LLNs). For that purpose, this document specifies a reactive P2P
   route discovery mechanism for both hop-by-hop routing and source
   routing: Ad Hoc On-demand Distance Vector Routing (AODV) based RPL
   protocol. Paired Instances are used to construct directional paths,
   in case some of the links between source and target node are
   asymmetric.

Status of This Memo

Table of Contents

1. Introduction

   RPL[RFC6550] is a IPv6 distance vector routing protocol for Low-power
   and Lossy Networks (LLNs), and is designed to support multiple
   traffic flows through a root-based Destination-Oriented Directed
   Acyclic Graph (DODAG). Typically, a router does not have routing
   information for most other routers. Consequently, for traffic
   between routers within the DODAG (i.e., Point-to-Point (P2P) traffic)
   data packets either have to traverse the root in non-storing mode, or
   traverse a common ancestor in storing mode. Such P2P traffic is
   thereby likely to traverse longer routes and may suffer severe
   congestion near the DAG root [RFC6997], [RFC6998].

   To discover better paths for P2P traffic flows in RPL, P2P-RPL
   [RFC6997] specifies a temporary DODAG where the source acts as a
   temporary root. The source initiates DIOs encapsulating the P2P
   Route Discovery option (P2P-RDO) with an address vector for both hop-
   by-hop mode (H=1) and source routing mode (H=0). Subsequently, each
   intermediate router adds its IP address and multicasts the P2P mode
   DIOs, until the message reaches the target node (TargNode), which
   then sends the "Discovery Reply" object. P2P-RPL is efficient for
   source routing, but much less efficient for hop-by-hop routing due to
   the extra address vector overhead. However, for symmetric links,
   when the P2P mode DIO message is being multicast from the source hop-
   by-hop, receiving nodes can infer a next hop towards the source.
   When TargNode subsequently replies to the source along the
   established forward route, receiving nodes determine the next hop
   towards TargNode. For hop-by-hop routes (H=1) over symmetric links,
   this would allow efficient use of routing tables for P2P-RDO messages
   instead of the "Address Vector".

   RPL and P2P-RPL both specify the use of a single DODAG in networks of
   symmetric links, where the two directions of a link MUST both satisfy
   the constraints of the objective function. This disallows the use of
   asymmetric links which are qualified in one direction. But,
   application-specific routing requirements as defined in IETF ROLL
   Working Group [RFC5548], [RFC5673], [RFC5826] and [RFC5867] may be
   satisfied by routing paths using bidirectional asymmetric links. For
   this purpose, [I-D.thubert-roll-asymlink] described bidirectional
   asymmetric links for RPL [RFC6550] with Paired DODAGs, for which the
   DAG root (DODAGID) is common for two Instances. This can satisfy
   application-specific routing requirements for bidirectional
   asymmetric links in core RPL [RFC6550]. Using P2P-RPL twice with

   Paired DODAGs, on the other hand, requires two roots: one for the
   source and another for the target node due to temporary DODAG
   formation. For networks composed of bidirectional asymmetric links
   (see Section 5), AODV-RPL specifies P2P route discovery, utilizing
   RPL with a new MoP. AODV-RPL makes use of two multicast messages to
   discover possibly asymmetric routes, which can achieve higher route
   diversity. AODV-RPL eliminates the need for address vector overhead
   in hop-by-hop mode. This significantly reduces the control packet
   size, which is important for Constrained LLN networks. Both
   discovered routes (upward and downward) meet the application specific
   metrics and constraints that are defined in the Objective Function
   for each Instance [RFC6552].

   The route discovery process in AODV-RPL is modeled on the analogous
   procedure specified in AODV [RFC3561]. The on-demand nature of AODV
   route discovery is natural for the needs of peer-to-peer routing in
   RPL-based LLNs. AODV terminology has been adapted for use with AODV-
   RPL messages, namely RREQ for Route Request, and RREP for Route
   Reply. AODV-RPL currently omits some features compared to AODV -- in
   particular, flagging Route Errors, blacklisting unidirectional links,
   multihoming, and handling unnumbered interfaces.

2. Terminology

   The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
   "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and
   "OPTIONAL" in this document are to be interpreted as described in
   [RFC2119]. This document uses the following terms:

   AODV
      Ad Hoc On-demand Distance Vector Routing[RFC3561].

   AODV-RPL Instance
      Either the RREQ-Instance or RREP-Instance

   Asymmetric Route
      The route from the OrigNode to the TargNode can traverse different
      nodes than the route from the TargNode to the OrigNode. An
      asymmetric route may result from the asymmetry of links, such that
      only one direction of the series of links fulfills the constraints
      in route discovery.

   Bi-directional Asymmetric Link
      A link that can be used in both directions but with different link
      characteristics.

   DIO
      DODAG Information Object

   DODAG RREQ-Instance (or simply RREQ-Instance)
      RPL Instance built using the DIO with RREQ option; used for
      control message transmission from OrigNode to TargNode, thus
      enabling data transmission from TargNode to OrigNode.

   DODAG RREP-Instance (or simply RREP-Instance)
      RPL Instance built using the DIO with RREP option; used for
      control message transmission from TargNode to OrigNode thus
      enabling data transmission from OrigNode to TargNode.

   Downward Direction
      The direction from the OrigNode to the TargNode.

   Downward Route
      A route in the downward direction.

   hop-by-hop routing
      Routing when each node stores routing information about the next
      hop.

   on-demand routing
      Routing in which a route is established only when needed.

   OrigNode
      The IPv6 router (Originating Node) initiating the AODV-RPL route
      discovery to obtain a route to TargNode.

   Paired DODAGs
      Two DODAGs for a single route discovery process between OrigNode
      and TargNode.

   P2P
      Point-to-Point -- in other words, not constrained a priori to
      traverse a common ancestor.

   reactive routing
      Same as "on-demand" routing.

   RREQ-DIO message
      An AODV-RPL MoP DIO message containing the RREQ option. The
      RPLInstanceID in RREQ-DIO is assigned locally by the OrigNode.

   RREP-DIO message
      An AODV-RPL MoP DIO message containing the RREP option. The
      RPLInstanceID in RREP-DIO is typically paired to the one in the
      associated RREQ-DIO message.

   Source routing

      A mechanism by which the source supplies the complete route
      towards the target node along with each data packet [RFC6550].

   Symmetric route
      The upstream and downstream routes traverse the same routers.

   TargNode
      The IPv6 router (Target Node) for which OrigNode requires a route
      and initiates Route Discovery within the LLN network.

   Upward Direction
      The direction from the TargNode to the OrigNode.

   Upward Route
      A route in the upward direction.

   ART option
      AODV-RPL Target option: a target option defined in this document.

3. Overview of AODV-RPL

   With AODV-RPL, routes from OrigNode to TargNode within the LLN
   network established are "on-demand". In other words, the route
   discovery mechanism in AODV-RPL is invoked reactively when OrigNode
   has data for delivery to the TargNode but existing routes do not
   satisfy the application's requirements. The routes discovered by
   AODV-RPL are not constrained to traverse a common ancestor. Unlike
   RPL [RFC6550] and P2P-RPL [RFC6997], AODV-RPL can enable asymmetric
   communication paths in networks with bidirectional asymmetric links.
   For this purpose, AODV-RPL enables discovery of two routes: namely,
   one from OrigNode to TargNode, and another from TargNode to OrigNode.
   When possible, AODV-RPL also enables symmetric route discovery along
   Paired DODAGs (see Section 5).

   In AODV-RPL, routes are discovered by first forming a temporary DAG
   rooted at the OrigNode. Paired DODAGs (Instances) are constructed
   according to the AODV-RPL Mode of Operation (MoP) during route
   formation between the OrigNode and TargNode. The RREQ-Instance is
   formed by route control messages from OrigNode to TargNode whereas
   the RREP-Instance is formed by route control messages from TargNode
   to OrigNode. Intermediate routers join the Paired DODAGs based on
   the rank as calculated from the DIO message. Henceforth in this
   document, the RREQ-DIO message means the AODV-RPL mode DIO message
   from OrigNode to TargNode, containing the RREQ option (see
   Section 4.1). Similarly, the RREP-DIO message means the AODV-RPL
   mode DIO message from TargNode to OrigNode, containing the RREP
   option (see Section 4.2). The route discovered in the RREQ-Instance
   is used for transmitting data from TargNode to OrigNode, and the

route discovered in RREP-Instance is used for transmitting data from
OrigNode to TargNode.

4. AODV-RPL DIO Options

4.1. AODV-RPL DIO RREQ Option

OrigNode sets its IPv6 address in the DODAGID field of the RREQ-DIO
message. A RREQ-DIO message MUST carry exactly one RREQ option.

```
 0                   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 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      | Option Length |S|H|X| Compr | L |   MaxRank   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Orig SeqNo  |                                               |
+-+-+-+-+-+-+-+-+                                               |
|                                                               |
|                                                               |
|            Address Vector (Optional, Variable Length)         |
|                                                               |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

            Figure 1: DIO RREQ option format for AODV-RPL MoP

OrigNode supplies the following information in the RREQ option:

Type
    The type assigned to the RREQ option (see Section 9.2).

Option Length
    The length of the option in octets, excluding the Type and Length
    fields. Variable due to the presence of the address vector and
    the number of octets elided according to the Compr value.

S
    Symmetric bit indicating a symmetric route from the OrigNode to
    the router transmitting this RREQ-DIO.

H
    Set to one for a hop-by-hop route. Set to zero for a source
    route. This flag controls both the downstream route and upstream
    route.

X
    Reserved.

Compr
   4-bit unsigned integer. Number of prefix octets that are elided
   from the Address Vector. The octets elided are shared with the
   IPv6 address in the DODAGID. This field is only used in source
   routing mode (H=0). In hop-by-hop mode (H=1), this field MUST be
   set to zero and ignored upon reception.

L

   2-bit unsigned integer determining the duration that a node is
   able to belong to the temporary DAG in RREQ-Instance, including
   the OrigNode and the TargNode. Once the time is reached, a node
   MUST leave the DAG and stop sending or receiving any more DIOs for
   the temporary DODAG. The definition for the "L" bit is similar to
   that found in [RFC6997], except that the values are adjusted to
   enable arbitrarily long route lifetime.

   * 0x00: No time limit imposed.
   * 0x01: 16 seconds
   * 0x02: 64 seconds
   * 0x03: 256 seconds

   L is independent from the route lifetime, which is defined in the
   DODAG configuration option. The route entries in hop-by-hop
   routing and states of source routing can still be maintained even
   after the DAG expires.

MaxRank
   This field indicates the upper limit on the integer portion of the
   rank (calculated using the DAGRank() macro defined in [RFC6550]).
   A value of 0 in this field indicates the limit is infinity.

Orig SeqNo
   Sequence Number of OrigNode, defined similarly as in AODV
   [RFC3561].

Address Vector
   A vector of IPv6 addresses representing the route that the RREQ-
   DIO has passed. It is only present when the 'H' bit is set to 0.
   The prefix of each address is elided according to the Compr field.

A node MUST NOT join a RREQ instance if its own rank would equal to
or higher than MaxRank. Targnode can join the RREQ instance at a
rank whose integer portion is equal to the MaxRank. A router MUST
discard a received RREQ if the integer part of the advertised rank
equals or exceeds the MaxRank limit. This definition of MaxRank is
the same as that found in [RFC6997].

4.2. AODV-RPL DIO RREP Option

   TargNode sets its IPv6 address in the DODAGID field of the RREP-DIO
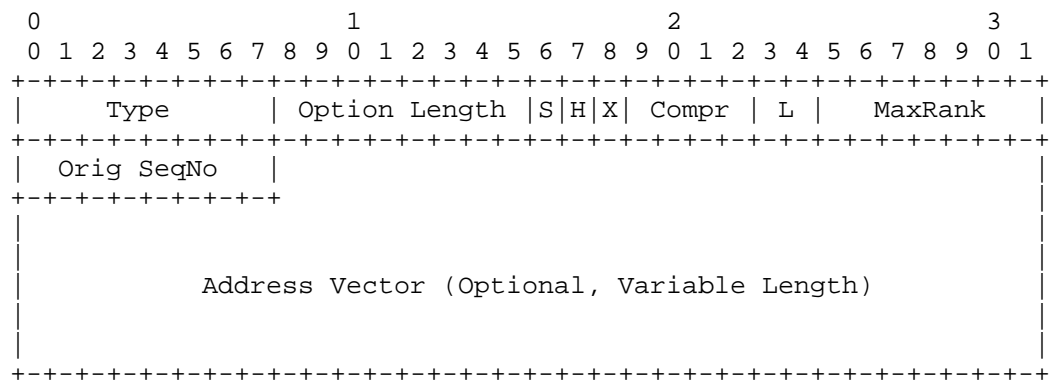   message. A RREP-DIO message MUST carry exactly one RREP option.
   TargNode supplies the following information in the RREP option:

```
 0                   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 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      | Option Length |G|H|X| Compr | L |   MaxRank   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Shift   |Rsv|                                              |
+-+-+-+-+-+-+-+-+                                              |
|                                                              |
|                                                              |
|            Address Vector (Optional, Variable Length)        |
.                                                              .
.                                                              .
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
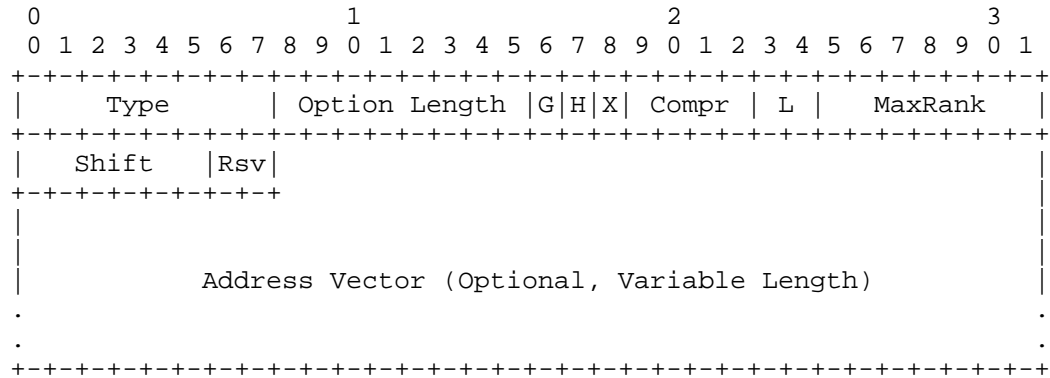
           Figure 2: DIO RREP option format for AODV-RPL MoP

   Type
      The type assigned to the RREP option (see Section 9.2)

   Option Length
      The length of the option in octets, excluding the Type and Length
      fields. Variable due to the presence of the address vector and
      the number of octets elided according to the Compr value.

   G
      Gratuitous route (see Section 7).

   H
      Requests either source routing (H=0) or hop-by-hop (H=1) for the
      downstream route. It MUST be set to be the same as the 'H' bit in
      RREQ option.

   X
      Reserved.

   Compr
      4-bit unsigned integer. Same definition as in RREQ option.

   L
      2-bit unsigned integer defined as in RREQ option.

   MaxRank

      Similarly to MaxRank in the RREQ message, this field indicates the
      upper limit on the integer portion of the rank. A value of 0 in
      this field indicates the limit is infinity.

   Shift
      6-bit unsigned integer. This field is used to recover the
      original InstanceID (see Section 6.3.3); 0 indicates that the
      original InstanceID is used.

   Rsv
      MUST be initialized to zero and ignored upon reception.

   Address Vector
      Only present when the 'H' bit is set to 0. For an asymmetric
      route, the Address Vector represents the IPv6 addresses of the
      route that the RREP-DIO has passed. For a symmetric route, it is
      the Address Vector when the RREQ-DIO arrives at the TargNode,
      unchanged during the transmission to the OrigNode.

4.3. AODV-RPL DIO Target Option

   The AODV-RPL Target (ART) Option is defined based on the Target
   Option in core RPL [RFC6550]: the Destination Sequence Number of the
   TargNode is added.

   A RREQ-DIO message MUST carry at least one ART Options. A RREP-DIO
   message MUST carry exactly one ART Option.

   OrigNode can include multiple TargNode addresses via multiple AODV-
   RPL Target Options in the RREQ-DIO, for routes that share the same
   constraints. This reduces the cost to building only one DODAG.
   Furthermore, a single Target Option can be used for different
   TargNode addresses if they share the same prefix; in that case the
   use of the destination sequence number is not defined in this
   document.

```
 0                   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 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      Type     | Option Length | Dest SeqNo  | Prefix Length |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               |
|                 Target Prefix (Variable Length)              |
.                                                               .
.                                                               .
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
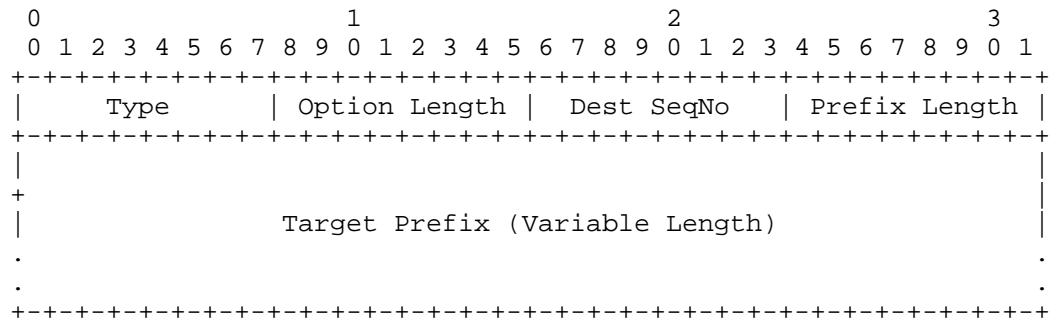
             Figure 3: Target option format for AODV-RPL MoP

    Type
       The type assigned to the ART Option

    Dest SeqNo

       In RREQ-DIO, if nonzero, it is the last known Sequence Number for
       TargNode for which a route is desired. In RREP-DIO, it is the
       destination sequence number associated to the route.

5. Symmetric and Asymmetric Routes

    In Figure 4 and Figure 5, BR is the Border Router, O is the OrigNode,
    R is an intermediate router, and T is the TargNode. If the RREQ-DIO
    arrives over an interface that is known to be symmetric, and the 'S'
    bit is set to 1, then it remains as 1, as illustrated in Figure 4.
    If an intermediate router sends out RREQ-DIO with the 'S' bit set to
    1, then all the one-hop links on the route from the OrigNode O to
    this router meet the requirements of route discovery, and the route
    can be used symmetrically.

```
                                 BR
                             /----+----\
                            /     |      \
                           /      |       \
                          R       R        R
                        _/ \      |      /  \
                        /   \     |     /    \
                       /     \    |    /      \
                      R ------- R --- R ----- R ------- R
                     / \   <--S=1-->  / \   <--S=1-->  / \
                <--S=1-->   \       /   \           /  <--S=1-->
                   /         \     /     \         /        \
                  O --------- R ----- R----- R ----- R --------- T
                / \          / \       / \       / \          / \
               /   \        /   \     /   \     /   \        /   \
              /     \      /     \   /     \   /     \      /     \
             R ----- R --------- R ----- R ----- R ----- R ---- R----- R

          >---- RREQ-Instance (Control: O-->T;  Data: T-->O) ------->
          <---- RREP-Instance (Control: T-->O;  Data: O-->T) ------<
```
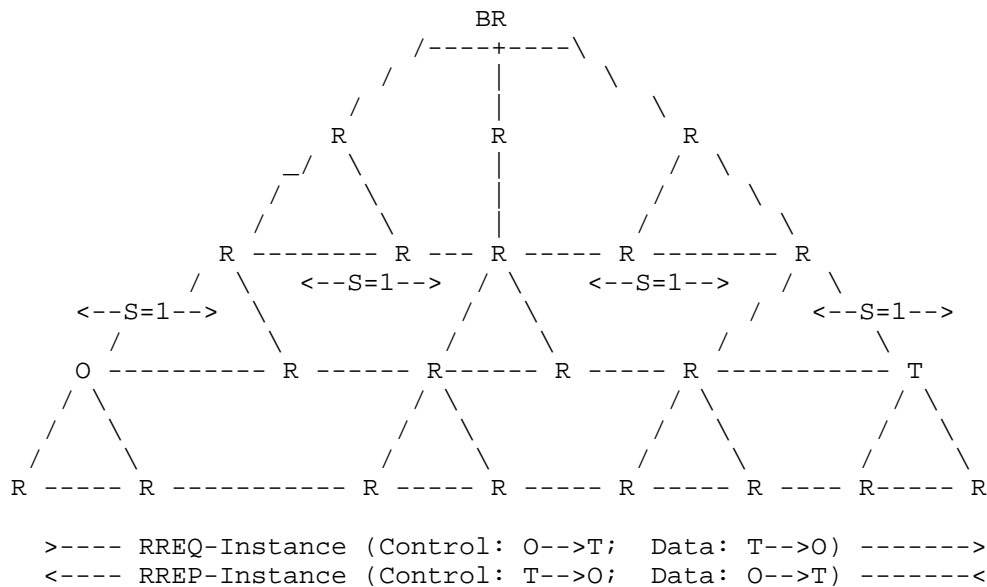
                Figure 4: AODV-RPL with Symmetric Paired Instances

   Upon receiving a RREQ-DIO with the 'S' bit set to 1, a node
   determines whether this one-hop link can be used symmetrically, i.e.,
   both the two directions meet the requirements of data transmission.
   If the RREQ-DIO arrives over an interface that is not known to be
   symmetric, or is known to be asymmetric, the 'S' bit is set to 0. If
   the 'S' bit arrives already set to be '0', it is set to be '0' on
   retransmission (Figure 5). Therefore, for asymmetric route, there is
   at least one hop which doesn't fulfill the constraints in the two
   directions. Based on the 'S' bit received in RREQ-DIO, the TargNode
   T determines whether or not the route is symmetric before
   transmitting the RREP-DIO message upstream towards the OrigNode O.

   The criteria used to determine whether or not each link is symmetric
   is beyond the scope of the document, and may be implementation-
   specific. For instance, intermediate routers MAY use local
   information (e.g., bit rate, bandwidth, number of cells used in
   6tisch), a priori knowledge (e.g. link quality according to previous
   communication) or use averaging techniques as appropriate to the
   application.

   Appendix A describes an example method using the ETX and RSSI to
   estimate whether the link is symmetric in terms of link quality is
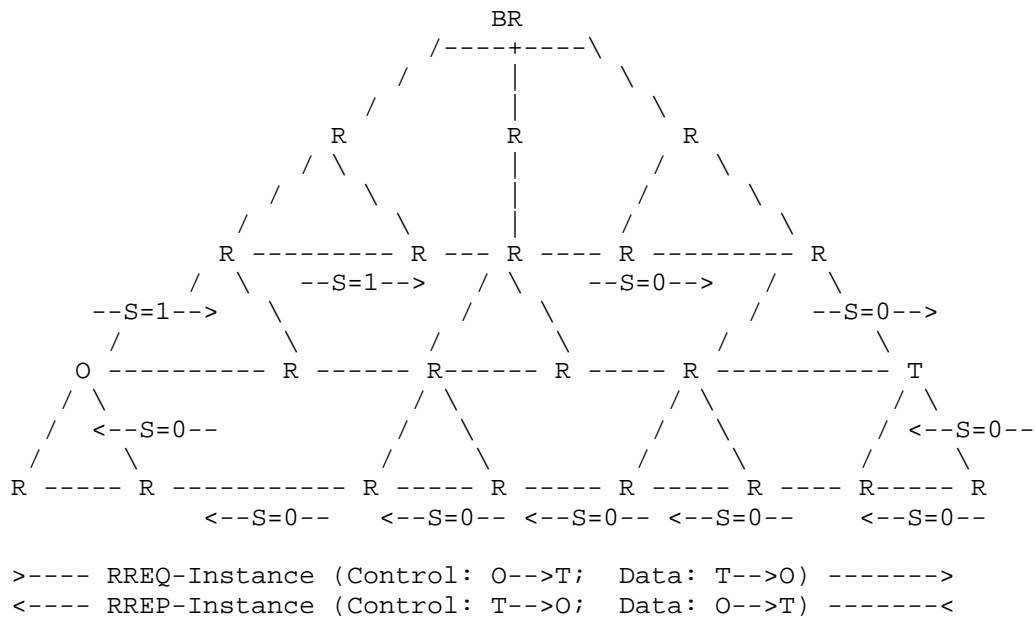   given in using an averaging technique.

```
                               BR
                         /----+----\
                        /     |      \
                       /      |       \
                      R       R        R
                     / \      |       / \
                    /   \     |      /   \
                   /     \    |     /     \
                  R --------- R --- R ---- R --------- R
                 / \    --S=1-->  / \    --S=0-->   /   \
              --S=1-->    \      /   \           /   --S=0-->
                /          \    /     \         /        \
               O --------- R ------ R------ R ----- R ---------- T
              / \          / \     / \     / \         / \
             /  <--S=0--  /   \   /   \   /   \       / <--S=0--
            /     \      /     \ /     \ /     \     /      \
           R ----- R ---------- R ----- R ----- R ----- R ---- R----- R
              <--S=0--    <--S=0-- <--S=0-- <--S=0--    <--S=0--

          >---- RREQ-Instance (Control: O-->T;  Data: T-->O) ------->
          <---- RREP-Instance (Control: T-->O;  Data: O-->T) -------<
```

            Figure 5: AODV-RPL with Asymmetric Paired Instances

6. AODV-RPL Operation

6.1. Route Request Generation

   The route discovery process is initiated when an application at the
   OrigNode has data to be transmitted to the TargNode, but does not
   have a route for the target that fulfills the requirements of the
   data transmission. In this case, the OrigNode builds a local
   RPLInstance and a DODAG rooted at itself. Then it transmits a DIO
   message containing exactly one RREQ option (see Section 4.1) via
   link-local multicast. The DIO MUST contain at least one ART Option
   (see Section 4.3). The 'S' bit in RREQ-DIO sent out by the OrigNode
   is set to 1.

   Each node maintains a sequence number, which rolls over like a
   lollipop counter [Perlman83], detailed operation can refer to the
   section 7.2 of [RFC6550]. When the OrigNode initiates a route
   discovery process, it MUST increse its own sequence number to avoid
   conflicts with previous established routes. The increased number is
   carried in the OrigSeqNo field of the RREQ option.

   The address in the ART Option can be a unicast IPv6 address or a
   prefix. The OrigNode can initiate the route discovery process for
   multiple targets simultaneously by including multiple ART Options,

and within a RREQ-DIO the requirements for the routes to different
TargNodes MUST be the same.

OrigNode can maintain different RPLInstances to discover routes with
different requirements to the same targets. Using the InstanceID
pairing mechanism (see Section 6.3.3), route replies (RREP-DIOs) for
different RPLInstances can be distinguished.

The transmission of RREQ-DIO obeys the Trickle timer. If the
duration specified by the "L" bit has elapsed, the OrigNode MUST
leave the DODAG and stop sending RREQ-DIOs in the related
RPLInstance.

6.2. Receiving and Forwarding RREQ messages

6.2.1. General Processing

Upon receiving a RREQ-DIO, a router which does not belong to the
RREQ-instance goes through the following steps:

Step 1:

If the 'S' bit in the received RREQ-DIO is set to 1, the router
MUST check the two directions of the link by which the RREQ-DIO is
received. In case that the downward (i.e. towards the TargNode)
direction of the link can't fulfill the requirements, the link
can't be used symmetrically, thus the 'S' bit of the RREQ-DIO to
be sent out MUST be set as 0. If the 'S' bit in the received
RREQ-DIO is set to 0, the router only checks into the upward
direction (towards the OrigNode) of the link.

If the upward direction of the link can fulfill the requirements
indicated in the constraint option, and the router's rank would
not exceed the MaxRank limit, the router joins the DODAG of the
RREQ-Instance. The router that transmitted the received RREQ-DIO
is selected as the preferred parent. Later, other RREQ-DIO
messages might be received. How to maintain the parent set,
select the preferred parent, and update the router's rank obeys
the core RPL and the OFs defined in ROLL WG. In case that the
constraint or the MaxRank limit is not fulfilled, the router MUST
discard the received RREQ-DIO and MUST NOT join the DODAG.

Step 2:

Then the router checks if one of its addresses is included in one
of the ART Options. If so, this router is one of the TargNodes.
Otherwise, it is an intermediate router.

Step 3:

   If the 'H' bit is set to 1, then the router (TargNode or
   intermediate) MUST build the upward route entry accordingly. The
   route entry MUST include at least the following items: Source
   Address, InstanceID, Destination Address, Next Hop, Lifetime, and
   Sequence Number. The Destination Address and the InstanceID can
   be respectively learned from the DODAGID and the RPLInstanceID of
   the RREQ-DIO, and the Source Address is copied from the ART
   Option. The next hop is the preferred parent. And the lifetime
   is set according to DODAG configuration and can be extended when
   the route is actually used. The sequence number represents the
   freshness of the route entry, and it is copied from the Orig SeqNo
   field of the RREQ option. A route entry with same source and
   destination address, same InstanceID, but stale sequence number,
   SHOULD be deleted.

   If the 'H' bit is set to 0, an intermediate router MUST include
   the address of the interface receiving the RREQ-DIO into the
   address vector.

Step 4:

   An intermediate router transmits a RREQ-DIO via link-local
   multicast. TargNode prepares a RREP-DIO.

6.2.2. Additional Processing for Multiple Targets

   If the OrigNode tries to reach multiple TargNodes in a single RREQ-
   instance, one of the TargNodes can be an intermediate router to the
   others, therefore it SHOULD continue sending RREQ-DIO to reach other
   targets. In this case, before rebroadcasting the RREQ-DIO, a
   TargNode MUST delete the Target Option encapsulating its own address,
   so that downstream routers with higher ranks do not try to create a
   route to this TargetNode.

   An intermediate router could receive several RREQ-DIOs from routers
   with lower ranks in the same RREQ-instance but have different lists
   of Target Options. When rebroadcasting the RREQ-DIO, the
   intersection of these lists SHOULD be included. For example, suppose
   two RREQ-DIOs are received with the same RPLInstance and OrigNode.
   Suppose further that the first RREQ has (T1, T2) as the targets, and
   the second one has (T2, T4) as targets. Then only T2 needs to be
   included in the generated RREQ-DIO. If the intersection is empty, it
   means that all the targets have been reached, and the router SHOULD
   NOT send out any RREQ-DIO. Any RREQ-DIO message with different ART
   Options coming from a router with higher rank is ignored.

6.3. Generating Route Reply (RREP) at TargNode

6.3.1. RREP-DIO for Symmetric route

   If a RREQ-DIO arrives at TargNode with the 'S' bit set to 1, there is
   a symmetric route along which both directions can fulfill the
   requirements. Other RREQ-DIOs might later provide asymmetric upward
   routes (i.e. S=0). Selection between a qualified symmetric route
   and an asymmetric route that might have better performance is
   implementation-specific and out of scope. If the implementation uses
   the symmetric route, the TargNode MAY delay transmitting the RREP-DIO
   for duration RREP_WAIT_TIME to await a better symmetric route.

   For a symmetric route, the RREP-DIO message is unicast to the next
   hop according to the accumulated address vector (H=0) or the route
   entry (H=1). Thus the DODAG in RREP-Instance does not need to be
   built. The RPLInstanceID in the RREP-Instance is paired as defined
   in Section 6.3.3. In case the 'H' bit is set to 0, the address
   vector received in the RREQ-DIO MUST be included in the RREP-DIO.
   The sequence number of the TargNode is updated to the maximum of its
   current sequence number and the Dest SeqNo in the ART option of the
   RREQ-DIO, using a mechanism similar to that used in [RFC3561]. This
   updated sequence number is then copied to the Dest SeqNo field of the
   ART option. The address of the OrigNode MUST be encapsulated in the
   ART Option and included in this RREP-DIO message.

6.3.2. RREP-DIO for Asymmetric Route

   When a RREQ-DIO arrives at a TargNode with the 'S' bit set to 0, the
   TargNode MUST build a DODAG in the RREP-Instance rooted at itself in
   order to discover the downstream route from the OrigNode to the
   TargNode. The RREP-DIO message MUST be re-transmitted via link-local
   multicast until the OrigNode is reached or MaxRank is exceeded.

   The settings of the fields in RREP option and ART option are the same
   as for the symmetric route, except for the 'S' bit.

6.3.3. RPLInstanceID Pairing

   Since the RPLInstanceID is assigned locally (i.e., there is no
   coordination between routers in the assignment of RPLInstanceID), the
   tuple (OrigNode, TargNode, RPLInstanceID) is needed to uniquely
   identify a discovered route. The upper layer applications may have
   different requirements and they can initiate the route discoveries
   simultaneously. Thus between the same pair of OrigNode and TargNode,
   there can be multiple AODV-RPL instances. To avoid any mismatch, the
   RREQ-Instance and the RREP-Instance in the same route discovery MUST
   be paired somehow, e.g. using the RPLInstanceID.

When preparing the RREP-DIO, a TargNode could find the RPLInstanceID
to be used for the RREP-Instance is already occupied by another RPL
Instance from an earlier route discovery operation which is still
active. In other words, it might happen that two distinct OrigNodes
need routes to the same TargNode, and they happen to use the same
RPLInstanceID for RREQ-Instance. In this case, the occupied
RPLInstanceID MUST NOT be used again. Then the second RPLInstanceID
MUST be shifted into another integer so that the two RREP-instances
can be distinguished. In RREP option, the Shift field indicates the
shift to be applied to original RPLInstanceID. When the new
InstanceID after shifting exceeds 63, it rolls over starting at 0.
For example, the original InstanceID is 60, and shifted by 6, the new
InstanceID will be 2. Related operations can be found in
Section 6.4.

6.4. Receiving and Forwarding Route Reply

Upon receiving a RREP-DIO, a router which does not belong to the
RREQ-instance goes through the following steps:

Step 1:

   If the 'S' bit is set to 1, the router proceeds to step 2.

   If the 'S' bit of the RREP-DIO is set to 0, the router MUST check
   the downward direction of the link (towards the TargNode) over
   which the RREP-DIO is received. If the downward direction of the
   link can fulfill the requirements indicated in the constraint
   option, and the router's rank would not exceed the MaxRank limit,
   the router joins the DODAG of the RREP-Instance. The router that
   transmitted the received RREP-DIO is selected as the preferred
   parent. Afterwards, other RREP-DIO messages can be received. How
   to maintain the parent set, select the preferred parent, and
   update the router's rank obeys the core RPL and the OFs defined in
   ROLL WG.

   If the constraints are not fulfilled, the router MUST NOT join the
   DODAG; the router MUST discard the RREQ-DIO, and does not execute
   the remaining steps in this section.

Step 2:

   The router next checks if one of its addresses is included in the
   ART Option. If so, this router is the OrigNode of the route
   discovery. Otherwise, it is an intermediate router.

Step 3:

If the 'H' bit is set to 1, then the router (OrigNode or
intermediate) MUST build a downward route entry. The route entry
SHOULD include at least the following items: OrigNode Address,
InstanceID, TargNode Address as destination, Next Hop, Lifetime
and Sequence Number. For a symmetric route, the next hop in the
route entry is the router from which the RREP-DIO is received.
For an asymmetric route, the next hop is the preferred parent in
the DODAG of RREQ-Instance. The InstanceID in the route entry
MUST be the original RPLInstanceID (after subtracting the Shift
field value). The source address is learned from the ART Option,
and the destination address is learned from the DODAGID. The
lifetime is set according to DODAG configuration and can be
extended when the route is actually used. The sequence number
represents the freshness of the route entry, and is copied from
the Dest SeqNo field of the ART option of the RREP-DIO. A route
entry with same source and destination address, same InstanceID,
but stale sequence number, SHOULD be deleted.

If the 'H' bit is set to 0, for an asymmetric route, an
intermediate router MUST include the address of the interface
receiving the RREP-DIO into the address vector; for a symmetric
route, there is nothing to do in this step.

Step 4:

If the receiver is the OrigNode, it can start transmitting the
application data to TargNode along the path as provided in RREP-
Instance, and processing for the RREP-DIO is complete. Otherwise,
in case of an asymmetric route, the intermediate router transmits
the RREP-DIO via link-local multicast. In case of a symmetric
route, the RREP-DIO message is unicast to the next hop according
to the address vector in the RREP-DIO (H=0) or the local route
entry (H=1). The RPLInstanceID in the transmitted RREP-DIO is the
same as the value in the received RREP-DIO. The local knowledge
for the TargNode's sequence number SHOULD be updated.

7. Gratuitous RREP

In some cases, an Intermediate router that receives a RREQ-DIO
message MAY transmit a "Gratuitous" RREP-DIO message back to OrigNode
instead of continuing to multicast the RREQ-DIO towards TargNode.
The intermediate router effectively builds the RREP-Instance on
behalf of the actual TargNode. The 'G' bit of the RREP option is
provided to distinguish the Gratuitous RREP-DIO (G=1) sent by the
Intermediate node from the RREP-DIO sent by TargNode (G=0).

The gratuitous RREP-DIO can be sent out when an intermediate router R
receives a RREQ-DIO for a TargNode T, and R happens to have a more

recent (larger destination sequence number) pair of downward and
upward routes to T which also fulfill the requirements.

In case of source routing, the intermediate router R MUST unicast the
received RREQ-DIO to TargNode T including the address vector between
the OrigNode O and the router R. Thus T can have a complete upward
route address vector from itself to O. Then R MUST send out the
gratuitous RREP-DIO including the address vector from R to T.

In case of hop-by-hop routing, R MUST unicast the received RREQ-DIO
hop-by-hop to T. The routers along the route SHOULD build new route
entries with the related RPLInstanceID and DODAGID in the downward
direction. Then T MUST unicast the RREP-DIO hop-by-hop to R, and the
routers along the route SHOULD build new route entries in the upward
direction. Upon receiving the unicast RREP-DIO, R sends the
gratuitous RREP-DIO to the OrigNode as defined in Section 6.3.

8. Operation of Trickle Timer

The trickle timer operation to control RREQ-Instance/RREP-Instance
multicast is similar to that in P2P-RPL [RFC6997].

9. IANA Considerations

9.1. New Mode of Operation: AODV-RPL

IANA is required to assign a new Mode of Operation, named "AODV-RPL"
for Point-to-Point(P2P) hop-by-hop routing under the RPL registry.
The value of TBD1 is assigned from the "Mode of Operation" space
[RFC6550].

```
+-------------+--------------+--------------+
|    Value    |  Description |   Reference  |
+-------------+--------------+--------------+
|   TBD1 (5)  |   AODV-RPL   | This document |
+-------------+--------------+--------------+
```

Figure 6: Mode of Operation

9.2. AODV-RPL Options: RREQ, RREP, and Target

Three entries are required for new AODV-RPL options "RREQ", "RREP"
and "ART" with values of TBD2 (0x0A), TBD3 (0x0B) and TBD4 (0x0C)
from the "RPL Control Message Options" space [RFC6550].

```
+-------------+----------------------+---------------+
|    Value    |       Meaning        |   Reference   |
+-------------+----------------------+---------------+
| TBD2 (0x0A) |     RREQ Option      | This document |
+-------------+----------------------+---------------+
| TBD3 (0x0B) |     RREP Option      | This document |
+-------------+----------------------+---------------+
| TBD3 (0x0C) |      ART Option      | This document |
+-------------+----------------------+---------------+
```

Figure 7: AODV-RPL Options

10. Security Considerations

This document does not introduce additional security issues compared
to base RPL. For general RPL security considerations, see [RFC6550].

11. Future Work

There has been some discussion about how to determine the initial
state of a link after an AODV-RPL-based network has begun operation.
The current draft operates as if the links are symmetric until
additional metric information is collected. The means for making
link metric information is considered out of scope for AODV-RPL. In
the future, RREQ and RREP messages could be equipped with new fields
for use in verifying link metrics. In particular, it is possible to
identify unidirectional links; an RREQ received across a
unidirectional link has to be dropped, since the destination node
cannot make use of the received DODAG to route packets back to the
source node that originated the route discovery operation. This is
roughly the same as considering a unidirectional link to present an
infinite cost metric that automatically disqualifies it for use in
the reverse direction.

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Appendix A. Example: ETX/RSSI Values to select S bit

   We have tested the combination of "RSSI(downstream)" and "ETX
   (upstream)" to determine whether the link is symmetric or asymmetric
   at the intermediate nodes. The example of how the ETX and RSSI
   values are used in conjuction is explained below:

        Source---------->NodeA---------->NodeB------->Destination

        Figure 8: Communication link from Source to Destination

   +------------------------+---------------------------------------+
   | RSSI at NodeA for NodeB | Expected ETX at NodeA for NodeB->NodeA |
   +------------------------+---------------------------------------+
> -60	150
-70 to -60	192
-80 to -70	226
-90 to -80	662
-100 to -90	993
   +------------------------+---------------------------------------+

          Table 1: Selection of 'S' bit based on Expected ETX value

   We tested the operations in this specification by making the
   following experiment, using the above parameters. In our experiment,

a communication link is considered as symmetric if the ETX value of
NodeA->NodeB and NodeB->NodeA (See Figure.8) are, say, within 1:3
ratio. This ratio should be taken as a notional metric for deciding
link symmetric/asymmetric nature, and precise definition of the ratio
is beyond the scope of the draft. In general, NodeA can only know
the ETX value in the direction of NodeA -> NodeB but it has no direct
way of knowing the value of ETX from NodeB->NodeA. Using physical
testbed experiments and realistic wireless channel propagation
models, one can determine a relationship between RSSI and ETX
representable as an expression or a mapping table. Such a
relationship in turn can be used to estimate ETX value at nodeA for
link NodeB--->NodeA from the received RSSI from NodeB. Whenever
nodeA determines that the link towards the nodeB is bi-directional
asymmetric then the "S" bit is set to "S=0". Later on, the link from
NodeA to Destination is asymmetric with "S" bit remains to "0".

Appendix B. Changelog

B.1. Changes to version 02

   o Include the support for source routing.

   o Import some features from [RFC6997], e.g., choice between hop-by-
      hop and source routing, the "L" bit which determines the duration
      of residence in the DAG, MaxRank, etc.

   o Define new target option for AODV-RPL, including the Destination
      Sequence Number in it. Move the TargNode address in RREQ option
      and the OrigNode address in RREP option into ADOV-RPL Target
      Option.

   o Support route discovery for multiple targets in one RREQ-DIO.

   o New InstanceID pairing mechanism.

B.2. Changes to version 03

   o Updated RREP option format. Remove the 'T' bit in RREP option.

   o Using the same RPLInstanceID for RREQ and RREP, no need to update
      [RFC6550].

   o Explanation of Shift field in RREP.

   o Multiple target options handling during transmission.

B.3. Changes to version 04

    o Add description for sequence number operations.

    o Extend the residence duration L in the section 4.1.

    o Change AODV-RPL Target option to ART option.

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