AODV based RPL Extensions for Supporting Asymmetric P2P Links in Low-Power and Lossy Networks
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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 (AODV-RPL). 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

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1. Introduction

   RPL [RFC6550] (Routing Protocol for Low-Power and Lossy Networks) is
   an IPv6 distance vector routing protocol 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 (for more information see [RFC6997],
   [RFC6998]).

   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.

   AODV-RPL reuses and provides a natural extension to the core RPL
   functionality to support routes with birectional asymmetric links.
   It retains RPL's DODAG formation, RPL Instance and the associated
   Objective Function, trickle timers, and support for storing and non-
   storing modes. AODV adds basic messages RREQ and RREP as part of RPL
   DIO (DODAG Information Object) control messages, and does not utilize
   the DAO message of RPL. AODV-RPL specifies a new MOP running in a
   seperate instance dedicating to discover P2P routes, which may differ
   from the P2MP routes discoverable by native RPL. AODV-RPL can be
   operated whether or not native RPL is running otherwise.

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 BCP

14 [RFC2119] [RFC8174] when, and only when, they appear in all
capitals, as shown here.

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 satisfies the Objective
    Function during 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 are established "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. AODV-RPL is thus functional
without requiring the use of RPL or any other routing protocol.

The routes discovered by AODV-RPL are not constrained to traverse a
common ancestor. 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 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,
otherwise it SHOULD be dropped.

```
      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
     +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
     |  Option Type  | Option Length |S|H|X| Compr | L |    MaxRank   |
     +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
     |  Orig SeqNo   |                                               |
     +-+-+-+-+-+-+-+-+                                               |
     |                                                               |
     |                                                               |
     |           Address Vector (Optional, Variable Length)          |
     |                                                               |
     |                                                               |
     +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

                 Figure 1: Format for AODV-RPL RREQ Option

   OrigNode supplies the following information in the RREQ option:

   Option Type
      TBD2

   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.

* 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 node no longer maintains DAG connectivity or messaging.

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. See Section 6.1.

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.

TargNode can join the RREQ instance at a Rank whose integer portion
is equal to the MaxRank. Other nodes MUST NOT join a RREQ instance
if its own Rank would be equal to or higher than MaxRank. A router
MUST discard a received RREQ if the integer part of the advertised
Rank equals or exceeds the MaxRank limit.

4.2. AODV-RPL RREP Option

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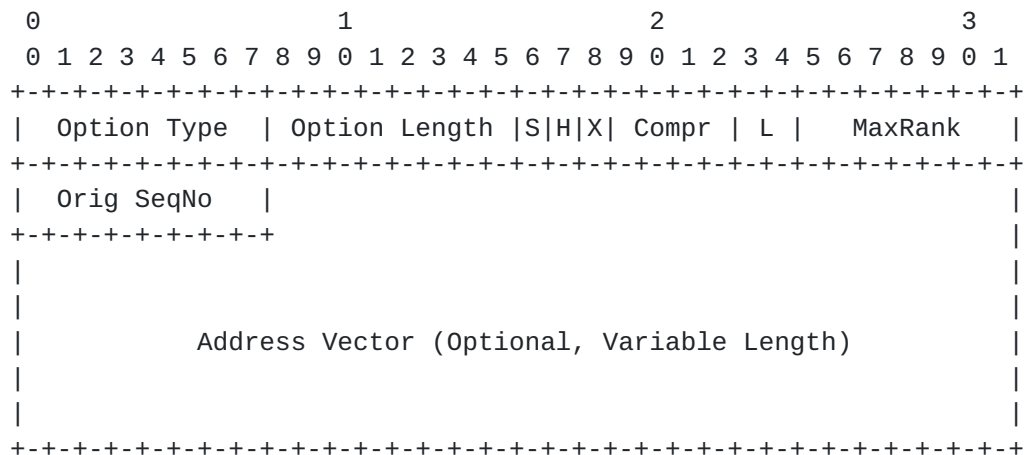message. A RREP-DIO message MUST carry exactly one RREP option,
otherwise the message SHOULD be dropped. TargNode supplies the
following information in the RREP option:

```
         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
         +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
         |  Option Type  | Option Length |G|H|X| Compr | L |    MaxRank    |
         +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
         |    Shift      |Rsv|                                            |
         +-+-+-+-+-+-+-+-+-+                                            |
         |                                                              |
         |                                                              |
         |             Address Vector (Optional, Variable Length)       |
         .                                                              .
         .                                                              .
         +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

                   Figure 2: Format for AODV-RPL RREP option

Option Type
   TBD3

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 RPLInstanceID (see Section 6.3.3); 0 indicates that the
original RPLInstanceID 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 Target Option

The AODV-RPL Target (ART) Option is based on the Target Option in
core RPL [RFC6550]. The Flags field is replaced by the Destination
Sequence Number of the TargNode and the Prefix Length field is
reduced to 7 bits so that the value is limited to be no greater than
127.

A RREQ-DIO message MUST carry at least one ART Option. A RREP-DIO
message MUST carry exactly one ART Option. Otherwise, the message
SHOULD be dropped.

OrigNode can include multiple TargNode addresses via multiple AODV-
RPL Target Options in the RREQ-DIO, for routes that share the same
requirement on metrics. This reduces the cost to building only one
DODAG.

```
    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
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   | Option Type  | Option Length |  Dest SeqNo   |r|Prefix Length|
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                                                               |
   |           Target Prefix / Address (Variable Length)           |
   .                                                               .
   .                                                               .
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
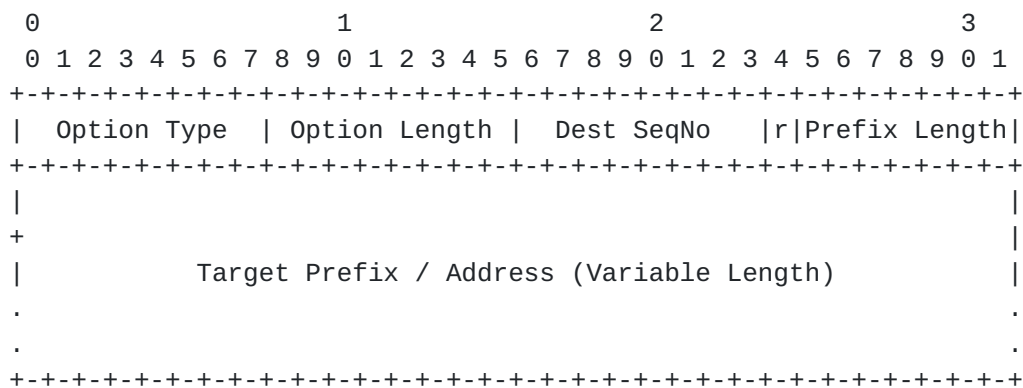
Figure 3: Target option format for AODV-RPL MOP

Option Type
TBD4

Option Length
   Length of the option in octets excluding the Type and Length
   fields

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.

r
   A one-bit reserved field. This field MUST be initialized to zero
   by the sender and MUST be ignored by the receiver.

Prefix Length
   7-bit unsigned integer. Number of valid leading bits in the IPv6
   Prefix. If Prefix Length is 0, then the value in the Target
   Prefix / Address field represents an IPv6 address, not a prefix.

Target Prefix / Address
   (variable-length field) An IPv6 destination address or prefix.
   The Prefix Length field contains the number of valid leading bits
   in the prefix. The length of the field is the least number of
   octets that can contain all of the bits of the Prefix, in other
   words Floor((7+(Prefix Length))/8) octets. The remaining bits in
   the Target Prefix / Address field after the prefix length (if any)
   MUST be set to zero on transmission and MUST be ignored on
   receipt.

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) ------->
```
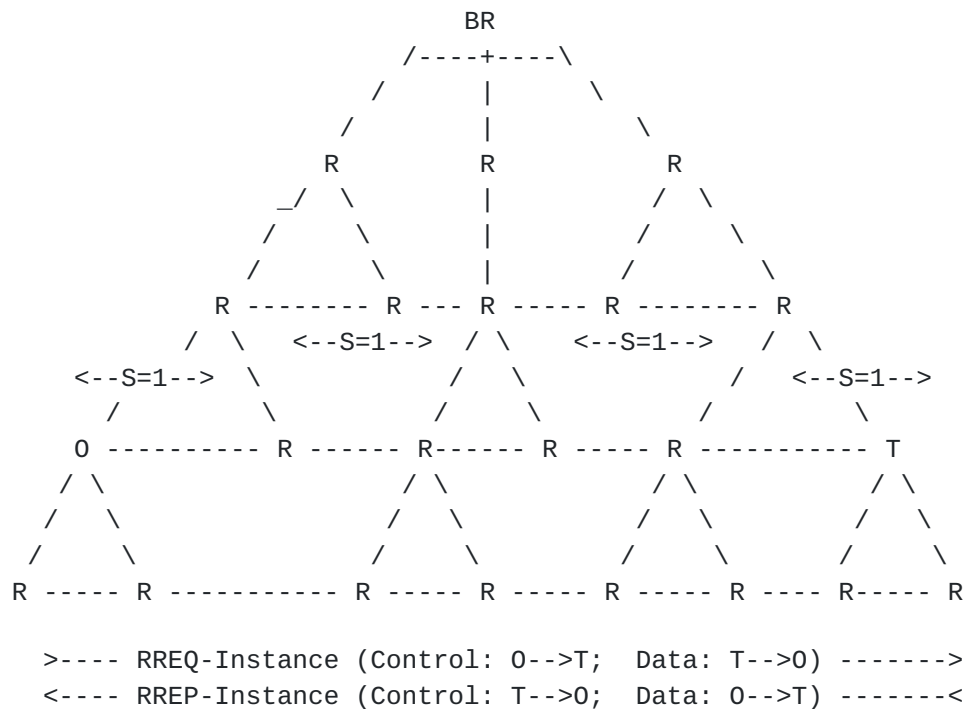
               Figure 4: AODV-RPL with Symmetric Paired Instances

   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). For an asymmetric route, there is at least one hop which
   doesn't satisfy the Objective Function. Based on the S bit received
   in RREQ-DIO, 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 can 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
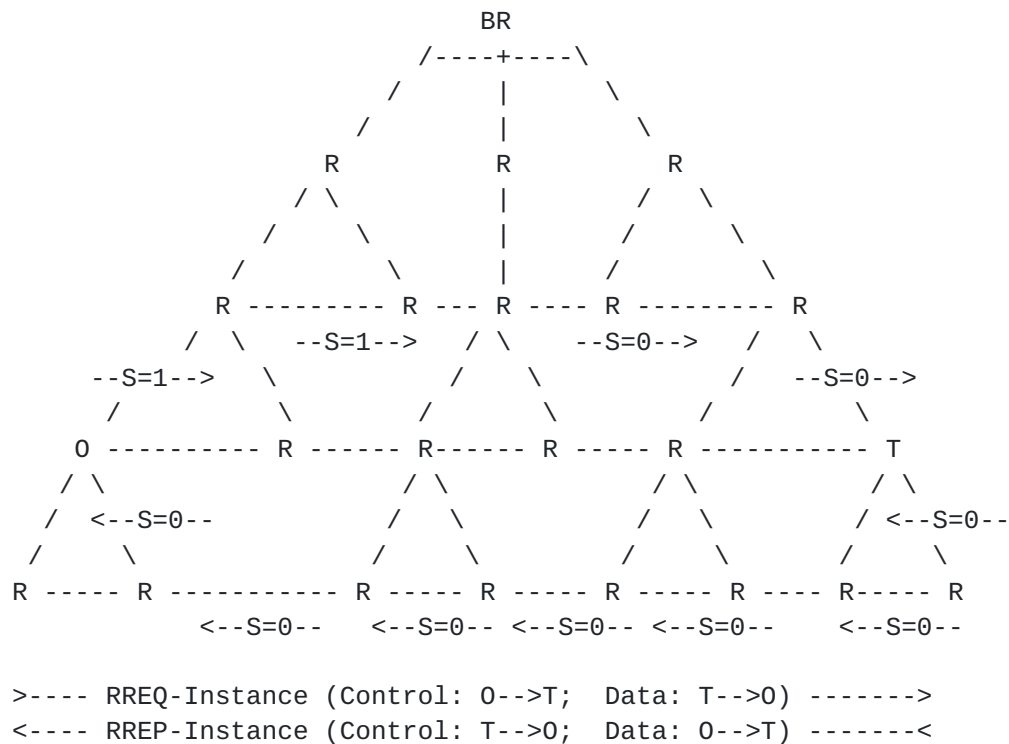   given in using an averaging technique.

```
                               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 that satisfies the Objective Function for the target 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; the operation is specified in
   section 7.2 of [RFC6550]. When the OrigNode initiates a route
   discovery process, it MUST increase its own sequence number to avoid
   conflicts with previously established routes. The sequence number is
   carried in the Orig SeqNo 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 [RFC6206]. 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 goes through the steps below. If
the router does not belong to the RREQ-Instance, then the maximum
useful rank (MaxUseRank) is MaxRank. Otherwise, MaxUseRank is set to
be the Rank value that was stored when the router processed the best
previous RREQ for the DODAG with the given RREQ-Instance.

Step 1:

   If the S bit in the received RREQ-DIO is set to 1, the router MUST
   determine whether each direction of the link (by which the RREQ-
   DIO is received) satisfies the Objective Function. In case that
   the downward (i.e. towards the TargNode) direction of the link
   does not satisfy the Objective Function, 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 MUST only check into the upward direction (towards the
   OrigNode) of the link.

   If the upward direction of the link can satisfy the Objective
   Function (defined in [RFC6551]), and the router's Rank would not
   exceed the MaxUseRank limit, the router joins the DODAG of the
   RREQ-Instance. The router that transmitted the received RREQ-DIO
   is selected as the preferred parent. Otherwise, if the Objective
   Function is not satisfied or the MaxUseRank limit is exceeded, 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 an upward route entry towards OrigNode
which MUST include at least the following items: Source Address,
InstanceID, Destination Address, Next Hop, Lifetime, and Sequence
Number. The Destination Address and the InstanceID respectively
can be learned from the DODAGID and the RPLInstanceID of the RREQ-
DIO, and the Source Address is the address used by the local
router to send data to the OrigNode. The Next Hop is the
preferred parent. The lifetime is set according to DODAG
configuration (i.e., not the L bit) 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 the same source and
destination address, same InstanceID, but stale sequence number,
MUST be deleted.

Step 4:

If the router is an intermediate router, then it transmits a RREQ-
DIO via link-local multicast; if the H bit is set to 0, the
intermediate router MUST include the address of the interface
receiving the RREQ-DIO into the address vector.. Otherwise, if
the router (i.e., TargNode) was not already associated with the
RREQ-Instance, it prepares a RREP-DIO Section 6.3. If, on the
other hand TargNode was already associated with the RREQ-Instance,
it takes no further action and does not send an 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 MUST 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 Rank values do not try to
create a route to this TargetNode.

An intermediate router could receive several RREQ-DIOs from routers
with lower Rank values in the same RREQ-Instance but have different
lists of Target Options. When rebroadcasting the RREQ-DIO, the
intersection of these lists MUST 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 MUST NOT
send out any RREQ-DIO. For the purposes of determining the
intersection with previous incoming RREQ-DIOs, the intermediate
router maintains a record of the targets that have been requested
associated with the RREQ-Instance. 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 satisfy the Objective
Function. 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
selects the symmetric route, and the L bit is not 0, the TargNode MAY
delay transmitting the RREP-DIO for duration RREP_WAIT_TIME to await
a symmetric route with a lower Rank. The value of RREP_WAIT_TIME is
set by default to 1/4 of the time duration determined by the L bit.

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. TargNode
increments its current sequence number and uses the incremented
result in the Dest SeqNo in the ART option of the RREQ-DIO. 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
TargNode MAY delay transmitting the RREP-DIO for duration
RREP_WAIT_TIME to await a route with a lower Rank. The value of
RREP_WAIT_TIME is set by default to 1/4 of the time duration
determined by the L bit.

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. It is possible that multiple route
discoveries with dissimilar Objective Functions are initiated
simultaneously. Thus between the same pair of OrigNode and TargNode,
there can be multiple AODV-RPL route discovery instances. To avoid
any mismatch, the RREQ-Instance and the RREP-Instance in the same
route discovery MUST be paired 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 MUST proceed 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 satisfy the Objective Function, 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.

If the Objective Function is not satisfied, 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
MUST 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.

Upon receiving a RREP-DIO, a router which already belongs to the
RREQ-Instance SHOULD drop the RREP-DIO.

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
receives a RREQ-DIO for a TargNode, and the router has a more recent
(larger destination sequence number) pair of downward and upward
routes to the TargNode which also satisfy the Objective Function.

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

In case of hop-by-hop routing, the intermediate router MUST unicast
the received RREQ-DIO to the Next Hop on the route. The Next Hop
router along the route MUST build new route entries with the related
RPLInstanceID and DODAGID in the downward direction. The above
process will happen recursively until the RREQ-DIO arrives at the
TargNode. Then the TargNode MUST unicast recursively the RREP-DIO
hop-by-hop to the intermediate router, and the routers along the
route SHOULD build new route entries in the upward direction. Upon
receiving the unicast RREP-DIO, the intermediate router 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 uses [RFC6206] to control RREQ-DIO and RREP-DIO
transmissions. The Trickle control of these DIO transmissions follow
the procedures described in the Section 8.3 of [RFC6550] entitled
"DIO Transmission".

9. IANA Considerations

9.1. New Mode of Operation: AODV-RPL

IANA is asked to assign a new Mode of Operation, named "AODV-RPL" for
Point-to-Point(P2P) hop-by-hop routing from the "Mode of Operation"
Registry [RFC6550].

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

Figure 6: Mode of Operation

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

IANA is asked to assign three new AODV-RPL options "RREQ", "RREP" and
"ART", as described in Figure 7 from the "RPL Control Message
Options" Registry [RFC6550].

```
+-------------+------------------------+---------------+
|    Value    |         Meaning        |   Reference   |
+-------------+------------------------+---------------+
| TBD2 (0x0A) |       RREQ Option      | This document |
+-------------+------------------------+---------------+
| TBD3 (0x0B) |       RREP Option      | This document |
+-------------+------------------------+---------------+
| TBD4 (0x0C) |       ART Option       | This document |
+-------------+------------------------+---------------+
```

Figure 7: AODV-RPL Options

10. Security Considerations

In general, the security considerations for the operation of AODV-RPL
are similar to those for the operation of RPL (as described in
Section 19 of the RPL specification [RFC6550]). Sections 6.1 and 10
of [RFC6550] describe RPL's security framework, which provides data
confidentiality, authentication, replay protection, and delay
protection services.

A router can join a temporary DAG created for a secure AODV-RPL route
discovery only if it can support the Security Configuration in use,
which also specifies the key in use. It does not matter whether the
key is preinstalled or dynamically acquired. The router must have

the key in use before it can join the DAG being created for a secure
P2P-RPL route discovery.

If a rogue router knows the key for the Security Configuration in
use, it can join the secure AODV-RPL route discovery and cause
various types of damage. Such a rogue router could advertise false
information in its DIOs in order to include itself in the discovered
route(s). It could generate bogus RREQ-DIO, and RREP-DIO messages
carrying bad routes or maliciously modify genuine RREP-DIO messages
it receives. A rogue router acting as the OrigNode could launch
denial-of-service attacks against the LLN deployment by initiating
fake AODV-RPL route discoveries. In this type of scenario, RPL's
authenticated mode of operation, where a node can obtain the key to
use for a P2P-RPL route discovery only after proper authentication,
SHOULD be used.

When RREQ-DIO message uses source routing option with 'H' set to 0,
some of the security concerns that led to the deprecation of Type 0
routing headers [RFC5095] may apply. To avoid the possibility of a
RREP-DIO message traveling in a routing loop, if one of its addresses
are present as part of the Source Route listed inside the message,
the Intermediate Router MUST NOT forward the message.

11. Link State Determination

This document specifies that links are considered symmetric until
additional information is collected. Other link metric information
can be acquired before AODV-RPL operation, by executing evaluation
procedures; for instance test traffic can be generated between nodes
of the deployed network. During AODV-RPL operation, OAM techniques
for evaluating link state (see([RFC7548], [RFC7276], [co-ioam]) MAY
be used (at regular intervals appropriate for the LLN). The
evaluation procedures are out of scope for AODV-RPL.

12. References

12.1. Normative References

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

   The combination of Received Signal Strength Indication(downstream)
   (RSSI) and Expected Number of Transmissions(upstream)" (ETX) has been
   tested to determine whether a link is symmetric or asymmetric at
   intermediate nodes. ETX and RSSI values may be used in conjunction
   as 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 within, say, a 1:3
   ratio. This ratio should be understood as determining the link's
   symmetric/asymmetric nature. NodeA can typically 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 0. Later on, the link from NodeA to Destination is asymmetric
with S bit remains set to 0.

Appendix B. Changelog

Note to the RFC Editor: please remove this section before
publication.

B.1. Changes from version 07 to version 08

   o Instead of describing the need for routes to "fulfill the
      requirements", specify that routes need to "satisfy the Objective
      Function".

   o Removed all normative dependencies on [RFC6997]

   o Rewrote Section 10 to avoid duplication of language in cited
      specifications.

   o Added Section 11 with text and citations to more fully describe
      how implementations determine whether links are symmetric.

   o Modified text comparing AODV-RPL to other protocols to emphasize
      the need for AODV-RPL instead of the problems with the other
      protocols.

   o Clarified that AODV-RPL uses some of the base RPL specification
      but does not require an instance of RPL to run.

   o Improved capitalization, quotation, and spelling variations.

   o Specified behavior upon reception of a RREQ-DIO or RREP-DIO
      message for an already existing DODAGID (e.g, Section 6.4).

   o Fixed numerous language issues in IANA Considerations Section 9.

   o For consistency, adjusted several mandates from SHOULD to MUST and
      from SHOULD NOT to MUST NOT.

   o Numerous editorial improvements and clarificaions.

B.2. Changes from version 06 to version 07

   o Added definitions for all fields of the ART option (see
      Section 4.3). Modified definition of Prefix Length to prohibit
      Prefix Length values greater than 127.

o Modified the language from [RFC6550] Target Option definition so
   that the trailing zero bits of the Prefix Length are no longer
   described as "reserved".

o Reclassified [RFC3561] and [RFC6998] as Informative.

o Added citation for [RFC8174] to Terminology section.

B.3. Changes from version 05 to version 06

o Added Security Considerations based on the security mechanisms
   defined in [RFC6550].

o Clarified the nature of improvements due to P2P route discovery
   versus bidirectional asymmetric route discovery.

o Editorial improvements and corrections.

B.4. Changes from version 04 to version 05

o Add description for sequence number operations.

o Extend the residence duration L in section 4.1.

o Change AODV-RPL Target option to ART option.

B.5. Changes from version 03 to version 04

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.6. Changes from version 02 to version 03

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.

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